UNIVERSITY OF CAPE TOWN
Department of Chemical Engineering

Life Cycle Sustainability Assessment of Next Generation Energy Infrastructure in Africa: Is there a case for Biohydrogen after Biomethane?

A thesis submitted for the fulfilment of the requirements of the degree of

Doctor of Philosophy

by

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Declaration by Author

I, Phumlani Masilela, declare that this thesis contains content of my own unaided work that I have carried out since the commencement of my PhD research study to date. It is submitted for the fulfilment of the requirements of the degree of Doctor of Philosophy in Chemical Engineering at the University of Cape Town.

Phumlani Masilela   16 August 2018

Dedication

Philippians 4:13 “I can do all things through Christ who strengthens me”. Amen!

This thesis is dedicated to my mother,

Jennifer Solani Masilela,

with love.

ABSTRACT

The recovery of energy in the form of biomethane gas from inexpensive biodegradable organic wastes is starting to become a cornerstone of green economy investments. It is possible that such installations could serve as a precursor for the infrastructural development of a hydrogen economy, since biogas processes can be modified to produce hydrogen instead of methane. It is unclear whether such a change would improve or worsen the environmental, social, and economic performance of such waste-to-energy installations. Earlier studies show that the dark fermentation process for biohydrogen production faces several challenges such as low yield and slower production rate. Furthermore, it is unclear whether the biohydrogen production technology offers potential benefits in terms of ecological and socioeconomic sustainability.

This study explores the usage of Life Cycle Sustainability Assessment (LCSA) to investigate next generation energy options to support green economies in Africa. LCSA has been advocated by the United Nations Environment Programme (UNEP) to consider the evaluation of all environmental, social and economic negative impacts and benefits in decision-making processes towards more sustainable products throughout their life cycle. This thesis uses LCSA for comparing biomethane versus biohydrogen produced from organic wastes in three settings: agro-industrial processing, represented by brewery wastewater; urban, represented by the organic fraction of municipal solid waste (OFMSW); and rural, represented by cattle manure. In each setting, two end-uses of both fuels are considered, viz. electricity generation (combined heat and power (CHP) systems vs. fuel cell (FC) systems), and as vehicle fuel (compressed natural gas (CNG) vehicles vs. fuel cell (FC) vehicles).

According to published information on biogas yields of the substrates (i.e. brewery wastewater, OFMSW, and cattle manure), biomethane achieve a significantly higher energetic yield than biohydrogen estimated at 9.0, 10.5, and 9.7 MJ/kg of volatile solids (VS) for the case of biomethane, and at 4.8, 1.4, and 0.9 MJ/kg of VS in the case of biohydrogen, for the three substrates respectively. This difference in energetic yields significantly impacts on all further sustainability performance of the fuels. Nevertheless, an LCSA comparison was constructed, combining environmental and social life cycle assessment with a life cycle cost calculation to present the overall sustainability performance index of the results.

The results show that for the urban setting (exemplified by OFMSW), the application of biomethane in CHP systems provides the highest sustainability performance index (SPI) value estimated at 1.90, while that of vehicle operations in CNG vehicles stands at 1.83. For biohydrogen, the recovery of energy from brewery wastewater in the agro-industrial setting (exemplified by brewery wastewater), the application of biohydrogen in the FC systems commands the SPI value of 1.75, but the vehicle operation in the FC vehicles records a much lower performance value of 0.90. The results clearly indicate that the biomethane technology for the electricity generation offers the most sustainable performance outcome when compared with the biohydrogen technology for the electricity generation which stands at 1.90 and 1.75, respectively. In the case of vehicles operations the application of biomethane in the CNG vehicles records much higher sustainability performance index value when compared to FC vehicles which stands at 1.83 and 0.90, respectively.

In the agro-industrial settings the application of the biomethane in the electricity generation systems is equal that of the application of the biomethane in the vehicle operations in the CNG vehicles, which stand at 1.73. In the case of the urban settings the application of biomethane in the electricity generations provides higher sustainability performance index value when compared to the vehicle operations in the CNG vehicles which records the value of 1.90 and 1.83, respectively. In rural settings (exemplified by cattle manure) the application of biomethane produced from cattle manure in CHP systems records high SPI value of 1.75, but application in the CNG vehicles records the SPI value estimated at 1.68. The outcomes of the study thus show that the generation and use of biomethane in all selected settings promises a better sustainability performance, when compared to biohydrogen. Agro-industrial settings, in particular, seem to be very well suited for biohydrogen production, and there is no strong case for the application of biohydrogen technology in both the urban and rural settings. It is observed that the life cycle cost performance is significantly influenced by the application of the fuel (i.e. either in electricity generation, or as fuel for vehicles), and not only by the type of technology implemented (i.e. anaerobic digestion vs. dark fermentation process). Clearly, decision making for implementation of a particular technology requires a sound decision on the demand of a particular fuel type, end application of the fuel and also the type of the technology implemented.

It has been reported that the energetic efficiencies in fuel cells for electrical energy generation has reached the efficiency of approximately 80%. The results of this study demonstrate that biohydrogen application for electricity generation seems to be promising for application in agro-industrial settings. This setting has access to skilled technicians required for the operating of the biohydrogen production technology, and also the economic power for the implementation of the biohydrogen technology. Often the implementation of the biomethane technology in the agro-industrial settings is to advance economic savings that result from the installations of the biogas digester. Thus, the private sector can either directly or indirectly play a crucial role in the research and development for the next energy generation infrastructural development.

The social aspects need to be considered when analysing the potential role of different energy technologies for sustainable development. Actually, people are accustomed to infrastructural development of biogas installation in rural areas when compared to the biohydrogen technology. The social performance in such settings is faced with serious challenges regarding the level of education among the people and availability of human capacity in terms of skill development for the implementation of the proper infrastructural development. In rural areas, there is a need to effectively pay attention to various stakeholders. It has been reported that in certain instances the energy generation technology can come to a halt if proper stakeholders and community leaders are not well informed about the plan to implement new energy generation technology.

This thesis thus demonstrates how UNEP's call to consider environmental, social and economic dimensions of new developments can be interpreted, with a special focus on technological advancement in energy production systems. The energy sector in Africa faces enormous twin challenges of making a leading development contribution whilst respecting environmental sustainability imperatives. This thesis provides realistic solutions and advice for policy development of implementation of renewable technological options in three types of African settings.

In respect to the development of the methodological approach for assessment of energy production systems, this study specifically contributed through developing a stakeholder analysis. The stakeholder analysis presents the framework for mapping of relevant impact indicators across the three dimension of sustainability analysis, for the production of gaseous energy carriers from organic wastes. The approach shows how different participating parties, such as government, companies primarily in the energy sector, end users (domestic users), and non-governmental organizations (NGOs) can collaborate and clearly understood impacts in the three dimension of sustainability. Furthermore, this developed stakeholder analysis within the context of LCSA has a role to play in the policy development by creating awareness between government, energy users and energy companies during energy technological innovations. The stakeholder analysis developed in this study was shown to help determine the social indicators within the context of LCSA.

In summary, while hydrogen may soon be applied as an energy carrier in practice, this thesis shows that as long as biohydrogen yields remain much lower than biomethane yields, there is no strong case for admitting biohydrogen technology in both urban and rural settings. At the moment it remains possible that biomethane infrastructural development could serve as a precursor for the infrastructural development for the biohydrogen technology in the agro-industrial settings.

ACKNOWLEDGEMENTS

Firstly, I would like to express my heartfelt gratitude to Prof. Harro von Blottnitz, not only for his valuable scientific input to my research work, but also his inexhaustible generosity and patience during the whole journey of my PhD course. He managed to turn every meeting into an uplifting session, and guided me towards completion of my PhD. Secondly, I also express my appreciation to Khataza “Humble” Makhubele for always been supportive and I could not have made it without your love and support.

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LIST OF OUTPUTS

2012 An investigation of the feasibility and desirability of using life cycle sustainability assessment for the next generation energy infrastructure in Africa: is there a case for biohydrogen after biomethane?
University of Cape Town, Department of Chemical Engineering on the 30th August 2012, Cape Town (Presentation).

2012 Comparative life cycle assessment of gaseous biofuels production from brewery wastewater.
SETAC Europe 18th LCA Case Study Symposium. The event was held in Copenhagen, Denmark, on 26-28 November 2012.
The theme of the conference was "Sustainability Assessment in the 21st century – tools, trends, and applications" (Presentation).

2013 Life cycle assessments of energy recovery from the organic fraction: biomethane or biohydrogen – for vehicle fuel or for electricity?
Proceedings of the 20th WasteCon Conference on 6 – 10 October 2014. Somerset West, Cape Town (Publication paper)

2015 The theme for the technical challenge the year was 'Engineering technology for a green economy'.
WomEng Fellowship Week, July 6 – 10, 2015, Bandwidth Barn, Cape Town (Presentation, workshop).

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GLOSSARY OF TERMS

Anaerobic digestion	Decomposition of organic matter by bacteria usually under wet conditions in the absence of oxygen (under low-oxygen) conditions. The organic decomposition under anaerobic conditions results in the generation of carbon dioxide (CO_2) and methane (CH_4).
Biofuel	Fuel produce directly or indirectly from biomass. The term biofuel applies to any solid, liquid, or gaseous fuel produced organic (once living) matter.
Biogas	A combustible gas derived from decomposing biological waste under anaerobic condition. Biogas normally consists of 50-60% methane, 25-50% carbon dioxide, and other possible elements such as nitrogen, hydrogen or oxygen.
Biohydrogen	Hydrogen produced biologically (mostly by bacteria) is called biological hydrogen or biohydrogen (Kovacs et al. 2000).
Biomass	Organic matter available on a renewable basis. Biomass includes forest and mill residues, agricultural crops and wastes, wood and wood wastes, animal wastes, livestock operation residues, aquatic plants, fast-growing trees and plants, and municipal and industrial wastes.
Biomethane	Biogas upgraded to natural gas quality. Biomethane is produced biologically by bacteria (Masilela 2011).
Digester	An airtight vessel or enclosure in which bacteria decompose biomass in wet condition to produce biogas.
Energy carrier	Substance or phenomenon that can be used to promote mechanical work or heat to operate chemical or physical processes.
Emissions	waste substances released into the air or water
Feedstock	A feedstock is any biomass resource destined for conversion to energy or biofuel.
Fuel	Synonym for final energy carriers.
Goal and scope definition	The first stage of the life cycle assessment (LCA) analysis, during which a series of theoretical parameters are defines, the goal of the study, its scope, the definition of the system to be examined and its boundaries, as well as the geographical coverage and functional unit used.
Interpretation of the results	The results are summarized and discussed as a basis of conclusions, recommendations and decision-making in accordance with the goal and scope definition.
Intermediate product	Input or output from a unit process which requires further transformation.
Life cycle assessment	The assessment of the environmental impact of a product or service through its lifespan.
Life cycle costing	A tool or technique that enables comparative cost assessment to be made over a specified period of time, taking into account all

	relevant economic factors both in terms of initial capital costs and future operational and asset replacement cost.
Life cycle inventory	Requires the detailed documentation of all materials (incl. Energy) and processes throughout the life cycle (from raw material acquisition to the production, use, end-of-life treatment, recycling and final disposal, i.e. cradle-to-grave).
Life cycle impact assessment	Calculation of impact assessment results across specific environmental impact categories and category indicators.
Life cycle sustainability assessment (LCSA)	LCSA is known as the holistic approach to evaluate environment, social, and economic impacts of a product or services with the objective to a more sustainable production and consumption of product through their life cycle" (Finkbeiner et al. 2010).
Social life cycle assessment (S-LCA)	Assesses the potential social impacts of products and relates to the different stakeholder groups affected by products, such as workers, local communities and consumers (UNEP 2009, Zamagni et al. 2011).
Sustainable development	Development that meets the needs of the present generation without compromising the needs of the future generations to meet their own needs (Brundtland 1987).
Thermophilic fermentation	Digestion in the range of 50-60 °C, but usually in the range of 50-55 °C.
Process energy	Energy input required for a unit process to operate the process or equipment within the process excluding energy input for production and delivery of this energy.
Unit process inventory	Inventory of energy and material flows (in-and output) which are used by a unit process.
Wheeling	The "free" movement of electricity or gas along interconnected transmission/transport (pipe-) lines of different owners for a certain transmission fee.

LIST OF ACRONYMS AND ABBREVIATIONS

AD	Anaerobic digestion
AFGBR	Anaerobic fluidized granular bed reactor
CHP	Combined heat and power
CNGV	Compressed natural gas vehicles
COD	Chemical oxygen demand
PBP	Payback period
GHG	Greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions and Energy Use in Transportation
IRR	Internal rate of return
ISO	International Standardization Organization
EoL	End of life
FU	Functional unit
kWh	Kilowatt hour
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCM	Life Cycle Management
MJ	Megajoules
MSW	Municipal solid waste
Nm^3	Normal cubic metre
NPV	Net present value
OFMSW	Organic fraction of municipal solid waste
SA	South Africa
SAP	Stakeholder analysis phase
SETAC	Society of Environmental Toxicology and Chemistry
SHDB	Social hotspots database
SLCA	Social Life Cycle Assessment
SLCIA	Social life cycle impact assessment
SPI	Sustainability Performance Index
UASB	Upflow anaerobic sludge blanket
UNEP	United Nations Environment Programme
VS	Volatile solids

1. CHAPTER 1: INTRODUCTION

1.1. Background

1.1.1. Overview of energy status and challenges in South Africa

To date fossil fuels such as coal, natural gas, and crude oil still play a huge role to drive the economies of many developed countries. South Africa is one of the African countries which depends heavily on these fossil fuels for energy generation -- see Figure 1.1 showing the country's energy mix (DoE 2009 and EIA 2015). Unfortunately, the use of fossil based fuels emits the carbon dioxide (CO_2), which is a precursor for climate change. However, the government over the past few years has been actively involved in creating one of the most progressive alternative energy programmes reduce or stabilize CO_2 emissions by 2025 (South Africa Yearbook 2013).

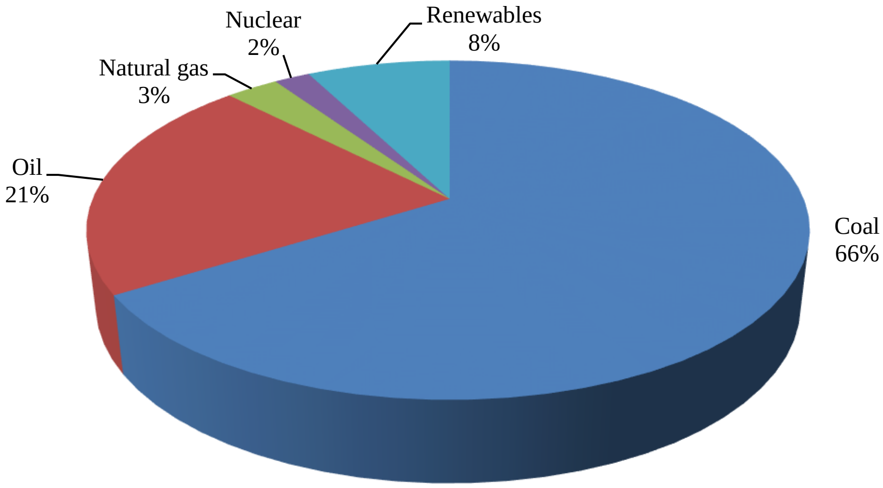

Figure 1.1: Total primary energy supply in South Africa 2011 (EIA 2015)

According to various reports the world is faced with challenges related to increase in the energy demand and population growth. The World Population Data Sheet report was published and estimated that the world population reached 7.3 billion in the year 2015, and is expected to increase to 9.8 billion by the year 2050. There are about 1.2 billion people currently residing in Africa, and this puts Africa as the second most populated continent in the world. The African population is also faced with rapid growth from 1.4 billion by 2025 to 2.2 billion by 2050 (Population Reference Bureau 2015). It is believed that the increasing population growth results in the increasing in the energy demand in the near future.

At the moment, most people are without electricity on the African continent. In fact the continent has the lowest electrification rates in the world, with only 43% of the population having access to grid electricity, leaving over 600 million people without access to electricity. The electrification in urban areas accounts for 70%, and only 28% of households in rural areas have access to grid electricity. In Sub-Sahara Africa the electricity shortage is startling with more than 80% of people primarily reliant on hazardous materials such as paraffin and wood for cooking and heating purposes. The use of these fuels in turn is responsible for serious environmental and human health problems in people's lives. Therefore, access to modern forms of energy services such as electricity is critical, and has a profoundly positive social and economic impact. It enables communities to power various activities, such as pumping water for irrigation, and powering essential health service, school buildings, and also households' energy needs (i.e. cooking, lighting, refrigeration, etc.).

In South Africa, electricity generation is dominated by state-owned enterprise Eskom, which currently produce over 96.7% of the power used in the country. Between 1994 and 2013/2014 just over 5.7 million households had been electrified, and it is estimated that about 3.2 million households still have no access to electricity (informal 1.2 million and 2 formal million), of which over 1 million are mostly situated in rural areas (Eskom 2013). The government has made tremendous progress in connecting millions of households to the national energy grid, but the fact remains that South Africa is facing mounting pressure on the national electricity grid.

The Department of Energy (DoE) announced a target to reach for renewable energy production at 10,000 GWh by December 2013. Unfortunately it was not achieved and the new target is set for the year 2025 (Department of Energy 2015). In the year 2013, Cabinet introduced a new electrification strategy and renewable energy is recognized to play a crucial role to achieve the universal access to electricity. According to the draft National Integrated Resource Plan for Electricity 6,000 GWh of this target is expected from on-grid electricity generation. The government supports various green energy initiatives for the deployment of renewable energy in South African energy mix. One of the progressive initiatives is the implementation of the Renewable Feed-In Tariff (REFIT) programme. The REFIT programme involved various stakeholders participating, but mostly private investments. Furthermore, South Africa is the only country which currently has a clear biofuels strategy when compared to other African countries.

1.1.2. Potential of renewable energy in South Africa and Africa

Renewable energy is reported as a clean energy source that could provide an opportunity to diversify the energy mix for many African countries. Some of the renewable energy resources that need to be exploited include hydro-power, solar energy, wind energy, geothermal energy and biofuels. Unfortunately, only less than 2% of renewable resources (excluding hydro) are exploited for electricity generation across Africa. Over the years biofuels have been receiving significant research attention, and currently the state of the art of biofuels considers the third-generation stage of biofuels, as seen in Figure 2.1. First-generation biofuels are widely available because the production technologies are well developed. However, growth of the raw materials conflicts with food security, so that first-generation biofuels are not so promising. The second generation of biofuels will not compete directly with food, but requires several energy-intensive processes to produce them, and also increases land-use change, which reduces its environmental and economic feasibility. The production of third-generation biofuels avoids the issues met with first- and second- generation biofuels (i.e. food–fuel competition, land-use change, etc.). Therefore, the third generation of biofuels are believed to be a viable alternative energy resource for production of renewable energy.

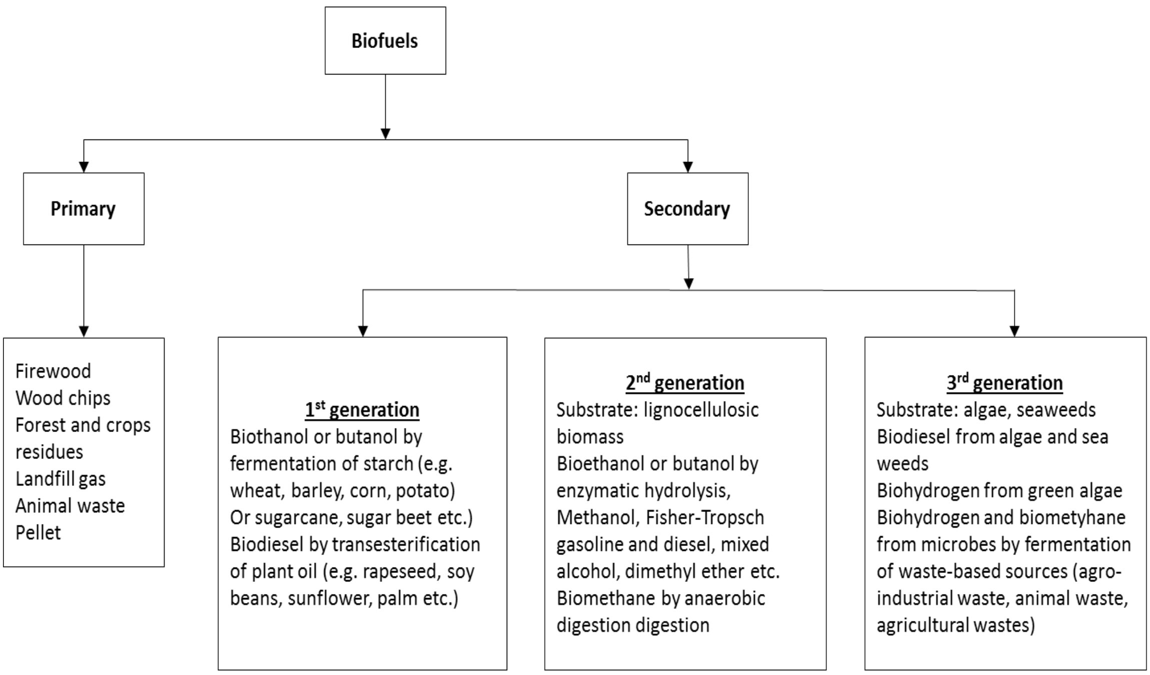

Figure 2.1: Evolution and generation of biofuels (Singh et al. 2011)

In recent years, studies have shown that actually some biofuels and their production and application might worsen the environmental performance as quantified by the Life Cycle Assessments (LCA). There is a growing concern about implementation of the unsustainable energy technologies. However, some biofuels such as biomethane and biohydrogen might carry lower sustainability risks because they can be generated from inexpensive organic waste residues rather than purposely grown plants (Melamu 2008). Biofuels are fuels derived from biomass or waste feedstock; some of the commonly known biofuels are bioethanol, biodiesel and gaseous biofuels (i.e. biomethane and biohydrogen). One challenge hindering biofuel development is implement biofuels with security, stable economic and social impacts (Singh et al. 2011).

The “Africa Biogas Partnership Programme” has set a mandate to install 2 million biogas digesters (i.e. biomethane digesters) by 2020 in different African countries. According to latest reports, the African Biogas Partnership Programme has sizeable numbers of installations in the following countries, including Kenya (15.980), Tanzania (12.160), Ethiopia (12.329), Uganda (6.169), and Burkina Faso (6.479) (ABPP 2017). It is estimated that there are currently 150 biogas digesters, for example including commercial facilities which are in operation across the country (Griffiths 2013). These digesters are based on a biological process known as anaerobic digestion (AD), whereby micro-organisms break down biodegradable material in the absence of oxygen to produce biogas. The biogas can either be used with minimal upgrading, for example for household lighting or cooking energy needs, or upgraded by purification before utilization for electricity generation (Amigun and Von Blottnitz 2010), or as transport fuel for compressed natural gas vehicles. It is important to realize that the world is shifting from solid to liquid to gaseous fuels (Hefner 2007) -- see Figure 3.1.

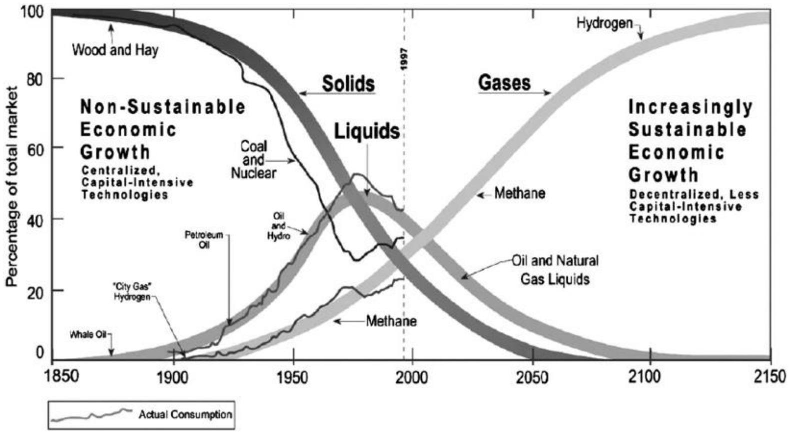

Figure 3.1: Global energy systems transition 1850-2150 (Hefner 2007)

In the light of a growing demand for renewable transportation fuels, a "hydrogen economy" remains an option also in Africa, with biohydrogen a possible improved version on first-generation biomethane investments. Interestingly, it is possible to modify anaerobic digestion (AD) technology to instead produce biohydrogen in a process known as anaerobic dark fermentation (ADF) technology. These can be achieved through manipulation of the bioreactor condition to support the growth of biohydrogen producing microorganisms, in simple term inhibition of methanogenesis. Both biomethane and biohydrogen can be produced in a similar process; however, biohydrogen is achieved at slightly higher temperatures (45-75 °C) and at different operational conditions from the methane-producing process. When comparing the biomethane and biohydrogen production technology, the thermophilic fermentation process is still at premature stage when compared to anaerobic digestion process. However, nowadays there are significant studies that have concluded that biohydrogen production technologies can be considered for large-scale biohydrogen production. Therefore, it will be interesting to see how the transition from biomethane towards biohydrogen economy is going to be reached.

It is believed that hydrogen offers system wide-energetic efficiency when compared to methane, especially in the application phase. According to Zhang (2011), some of the interesting features of hydrogen include: First, hydrogen has highest energy density per unit weight (142 MJ/kg) compared to all other fuel. Second, it has superior efficiency in energy conversion when used in fuel cells for power generation or in transport. Third, hydrogen combustion only produces water, meaning it achieves zero pollutants emission during the energy conversion process.

Gas production technologies such as anaerobic digestions have been successfully exploited in other countries like Germany and China. Despite having significant potential, South Africa still lags behind in comparison to other African countries to implement these technologies. This is unfortunate considering the fact that the country is the largest emitter of CO_2 in Africa and one of the largest economies in Africa. However, lately there has been a significant and increasing investment into renewable energy projects through various governments' initiatives. Through these projects there had been a progressive increase in job creation numbers in rural areas where unemployment is felt the most. Most of biogas digester installations are gaining increasing recognition in rural area, because of the abundant of various organic wastes that have not been adequately exploited for energy production. As these projects use cow dung, pig manure, kitchen waste and agricultural organic wastes to produce biogas through anaerobic digestion. This presents local people with modern energy sources and economic opportunities, as waste material are readily available to many in rural and urban area.

Clearly, there is energy technological revolution development in many rural communities, and anaerobic digestion is on the forefront to diversify the energy system of the country. These technologies enable societies to achieve sustainable development (i.e. improving living conditions) and improve economic development in the societies. However, the best energy generation technology is the one that lies towards the cost-effective horizon, producing the products in a sustainable manner. It includes taking into account the entire production chain of the product, including better capital investments, operation efficiencies, logistical challenges, distribution infrastructure, etc. The core function of the technology is to bring about a product with economical sensible practice in a sustainable manner. This will depend largely on the infrastructural development that is available in the region for the installation of the biogas producing plant. The infrastructural development needs to be clearly defined and established in order to support the implementation of the sustainable energy fuel production. It is important to note that the energy infrastructural development not only refers to the construction material but also considers the region's readiness for the construction and installation and operation of the biogas infrastructure. The infrastructural development should be inclusive of construction of viable commercial biogas, social infrastructure and the region's readiness (policy development, power and utility agreement, licensing and regulatory framework, etc.).

1.1.3. Transforming waste to energy: Anaerobic digestion/dark fermentation process

Today the production of biogas, also known as biomethane from various organic wastes through an anaerobic digestion (AD) process, has drawn significant attention. AD is a process whereby organic materials (such as biomass, sewage sludge, etc.) are biodegraded by microorganisms in an absence of oxygen to produce biogas, also known as biomethane. There are three types of AD processes, classified on the basis of the operating temperature, namely: psychrophilic (temperature of 10 - 25 °C), mesophilic (temperature of 25 -45 °C), and thermophilic (temperature of 45 - 65 °C).

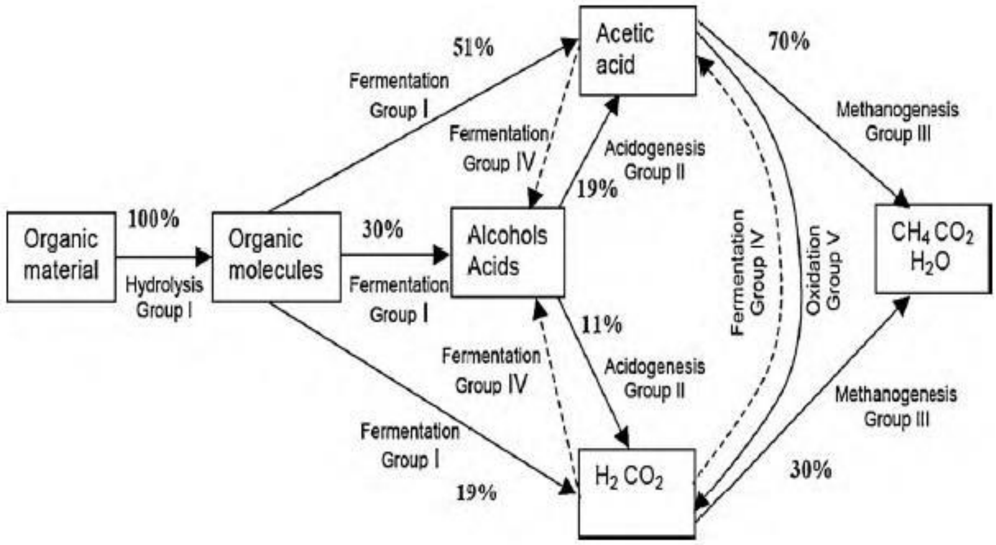

Figure 4.1: Different stages of anaerobic digestion process (adopted from Amigun and Von Blottnitz 2010)

Anaerobic digestion (AD) is a process commonly used for the treatment of different kinds of organic wastes. This process is complex -- Figure 4.1 represents the metabolic degradation pathway of the anaerobic digestion and fermentation process. There are four main groups of bacteria that play a crucial role; the metabolic steps include hydrolysis, acidogenic, acetogenic and methanogenic bacteria. Hydrolysis is the first step; here insoluble complex organic compounds (i.e. cellulose, carbohydrates etc.) are broken down into smaller soluble monomers (glucose, fatty acids and amino acids). Monomers from hydrolysis are synthesized into organic acids in acidogenesis. Organic acids are used as substrates to produce biohydrogen, carbon dioxide and mainly acetate in acetogenesis. Finally, biomethane and carbon dioxide are produced from acetate by different types of methanogenic bacteria.

During anaerobic treatment of organic wastes, acidogenesis is the second phase of the process, after initial hydrolysis, when volatile fatty acids (VFAs), alcohols, and gaseous biofuels (i.e. biomethane and biohydrogen) are produced. Therefore, it is important to inhibit the fourth stage, the methanogens, which is the stage that involves various microbial activities to convert the produced intermediate into biomethane. The inhibition of biomethane involves a great deal of operational parameters manipulation. Also, methanogenic microbial activity is inhibited at elevated temperatures, but also operational parameters such as pH, hydraulic retention time (HRT), etc. Temperature is another important parameter for biohydrogen production process control. This presents a relatively higher temperature of 50–60 °C can significantly improve the hydrogenase activity, metabolic pathway and microbial community structure, and thus promote the hydrogen production (Masilela 2011).

It also means biogas can be used to produce energy in the form of heat, combined heat and power (CHP) for electricity or as a vehicle fuel. One of the distinct advantages of a biogas plant as a renewable energy solution is its ability to be located anywhere a waste feedstock is available. There is no doubt that biomethane production system has been playing a crucial role in our energy system to drive economies. In light of growing demand for transportation fuels, biohydrogen is proposed as the most suitable fuel in comparison to biomethane. Table 1.1 shows the comparison of the biohydrogen and biomethane on the basis of their development and fuel properties. Biohydrogen has the highest energy content when compared to biomethane (i.e. 120 and 50 MJ/kg fuels, respectively). The purpose of a hydrogen fuel cell is to produce an electric current that can be used to do work. It includes a hydrogen fuel cell produces electric current by converting chemical energy into electrical energy and heat in a process that is virtually free of pollutants.

Table 1.1: Comparison of gaseous biofuels (i.e. biomethane and biohydrogen) and their application options

	Biomethane	**Biohydrogen**
Technology status	Conventional technology	New technology
Source	Food waste, agro-industrial waste, etc.	Food waste, agro-industrial waste, etc.
Production efficiencies	Higher	Low
Current development in SA	100 small/medium plants and 10 commercial scale	Laboratory experiments
Fuel properties (LHV)	50 MJ/kg	124 MJ/kg

Hydrogen has high energetic efficiency in fuel cell vehicles when compared to biomethane fuel. However, the thermophilic fermentation process is still in its infancy stage when compared to the anaerobic digestion (AD) process. In an attempt to optimize the thermophilic fermentation process, improvement of the bioprocess could be achieved by optimizing the reactor configuration and operational approach. Nowadays, there are significant report studies that have concluded that biohydrogen production technologies can be considered on a large scale. Biohydrogen is seen as the significant energy carrier to play a crucial role in world economies.

Since the AD technology is highly versatile, and can be adopted at different scales, viz. at household, medium and industrial scales, it lends itself to a variety of designs. As a result, AD systems vary widely, based on the scale of application. On the smaller scale, common designs include: fixed domes, floating drums and bladder digesters. On the larger scale, plug flow, up-flow anaerobic sludge blanket and Continuous Stirred Tank Reactor (CSTR) types of digesters are commonly found. These types of digesters differ in terms of application, operational and production efficiencies, as does their effect on the environment (either positive or negative) and resource consumption (i.e. energy, water, raw material – either fossil or renewable, etc.). The best technology offers an opportunity for efficient utilization of resources and produces the same product in a sustainable manner. Different technologies have distinct operating or manufacturing costs, including costs such as taxes, insurances, utility costs, labour requirements, local wage scale and maintenance, etc. Often, the core function of the technology is to bring about a product with environmentally and economically sensible practice. Therefore, it will be interesting to see how the transition from biomethane towards biohydrogen economy will be reached in terms of technological development and implementation.

1.1.4. Organic wastes for gaseous biofuels production

The United Nations Environment Programme (UNEP) published a guideline or framework for waste and climate change (UNEP 2013). The guidelines embrace the “waste management hierarchy,” best described as “the waste hierarchy is valuable conceptual and political prioritization tool which can assist in developing waste management strategies aimed at limiting resources consumption and protecting the environment”. According to the waste management hierarchy the following order is preferred when dealing with waste in the waste sector: waste minimization, re-use, and recycling, energy recovery, and treatment and disposal -- see Figure 5.1. This thesis considers the term “biowaste”, simply referring to biodegradable material such as food, paper, wood, and garden wastes. Therefore, various biowaste resources are utilized to produce useful energy fuel, and this also has the potential to contribute in the global greenhouse gas (GHG) reductions.

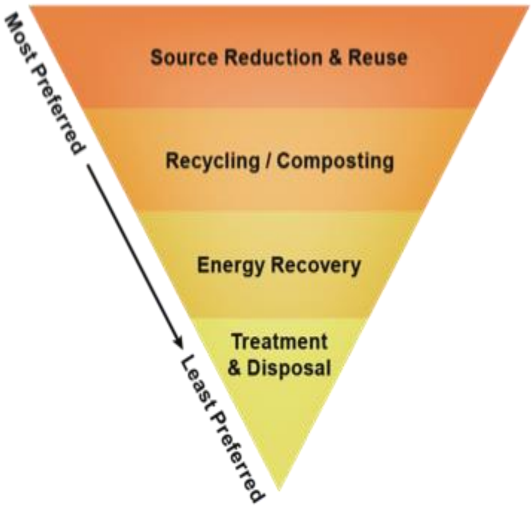

Figure 5.1: Waste management hierarchy (GreenCape 2016)

Any biodegradable waste contains organic material which can be decomposed under anaerobic or aerobic conditions by microbial communities to produce biogas (i.e. methane-rich biogas), and other trace amounts of gaseous products. Nowadays, it is important to realize that biowaste has become a valuable resource, and can be channelled in energy recovery systems rather than simply be disposed into landfills or municipal treatment works. According to Melamu (2008), production of gaseous biofuels from organic wastes carries lower sustainability risks, when compared to purposely grown plants. The utilization of organic wastes for energy generation has several advantages such as energy production, waste management solution, and contribute to climate change reductions. In this thesis, the following organic wastes are considered in energy production systems (i.e. brewery wastewater, organic fraction of municipal solid waste, cattle manures). Nowadays, waste-based residues are starting to receive attention for the renewable energy production because they do not compete with food for land.

Brewery wastewater

In South Africa, the South African Breweries (SAB) Company is one of the world's largest brewers and has several plants in various provinces across the country. It has been reported that one of these plants situated in Newlands, Cape Town, discharged approximately 380 425 kL/month, or an average of 1041 kL/d in 2010 (Dewing 2006). Often brewery effluent is disposed directly into sewage treatment works, or treated in anaerobic digesters. Lately, the company has installed anaerobic digester systems on the production site to produce biogas. The treated brewery wastewater from the digester is often disposed directly to sewage works, after it has been pre-treated to lower the chemical oxygen demand (COD). According to various reports from the company, this has led to various economic and environmental benefits as a result of the installation of the digester system on sites to treat the brewery wastewater (Cilliers 2012; Dewing 2006).

Organic fraction municipal solid waste (OFMSW)

Another important waste-based residue to consider is the organic fraction of municipal solid waste (OFMSW), which is a product from households. About 3.8 million tons of wastes were generated in the Western Cape in 2010 (Malla 2012). Further projections indicate that waste generation will reach 4.7 million tons and 5.2 tons per annum in 2015 and 2020 respectively. It has been reported that the City of Cape Town sends about 1.6 million tons of waste to landfills each year, of which 11% consists of compostable organic waste. This is equivalent to an estimated average of 21 kg/household/month of organic waste that ends up in landfill. Municipalities across the country propose a plan to divert OFMSW from the landfills, and one way is through various technologies such as anaerobic digestion. It is important to highlight that OFMSW can be diverted and used into waste-to-energy technologies to produce valuable energetic products, such as biomethane and biohydrogen.

Cattle manure

The use and exploitation of non-renewable resources is a responsible action which takes into account the consequences of the depletion of the resource and environmental concerns. Implementing “Waste-to-Energy” options offers advantages to avoid, or reuse of waste before being disposed in a responsible manner. Currently, the waste management practices are less effective and hold potential for environmental and health problems. In terms of waste management, the installation of a biogas facility provides a major improvement on the current farming and feedlot waste management practices. Cattle manure is very common in farms and in rural areas where there is a significant number of cattle at the site, so that the supply of animal manure should be significant at the site.

1.1.5. South African renewable energy policies and biogas sector overview

Over the past few years, the South African government has been at the forefront in developing several renewable energy policies and targets for implementation. In the year 2007, the government established the Biofuel Industrial Strategy, aiming to promote the production and the use of biomass fuels (Department of Minerals and Energy 2007). The White Paper on Renewable Energy of 2004 proposed the exploits of renewable energy to produce a renewable target of 10 000 GWh (mainly from biomass, wind, solar and small-scale hydro) by 2013 (Department of Minerals and Energy 2003). This is equivalent to about 5% of all electricity produced in South Africa at present, which is enough to replace two 660-MW units of Eskom's combined coal-fired power stations.

Recent development – the Renewable Energy Independent Power Programme (REIPPP), as outlined in the Integrated Resource Plan (IRP) 2010 -- highlights key determination from the government to increase the share of energy generated from low carbon sources by 40 000 MW. Of this, about 17 900 MW will be generated from renewable energy resources, 2 600 MW from imported hydro and 9 600 MW from nuclear (Eberhard et al. 2014). The Department of Energy (DoE) has a sole mandate to promote use of renewable energy, initiate projects to advance the use of renewable energy and annual monitor the precise quantity of energy produced from renewable energy. The Department of Energy (DoE) is proactively moving the economy towards becoming less carbon-intensive, with the DoE playing a prominent role.

According to the Integrated Resource Plan (IRP), the nuclear is envisage to contribute about 9 600 MW additional nuclear capacity by 2030. Biogas, small-scale hydro and landfill gas are still lagging behind. The IRP 2010 estimated that electricity demand by 2030 would require an increase in additional generation capacity of 52GW, 17.8GW of which will be from renewable sources – wind, solar, biomass, small-scale hydro and biogas, and 2.6GW from large-scale hydro (Eskom 2013). The Southern African Biogas Industry Association (SABIA) estimates that biogas can contribute 2.5GW generation capacity in the country, employing waste streams from wastewater treatment plants, food waste, and manure, agricultural waste and commercial processes including abattoirs, breweries and cheese factories (SABIA 2017).

In recognition of the barriers to biogas capacity development, the Department of Energy (DoE) facilitated the establishment of a National Biogas Platform in 2013 and have collaborated with SABIA to host two biogas conferences in 2013 and 2015, respectively. The National Biogas Platform was established with the aim to support and stimulate the development of South Africa's fledgling biogas industry. A national biogas strategy was developed by the Department of Energy (DoE) in collaboration with Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) (DoE 2015; Giljova 2013; Giljova 2015; South African-German Energy Programe 2013).

1.1.6. Life cycle thinking and sustainable development

Life cycle thinking (LCT) has become an important tool to understand how socio-technical systems affect the environment and even has a Wikipedia entry which defines it as "the approach of becoming mindful of how everyday life affects the environment" but in a way that the entire system behind the product or activity is considered (Wikipedia LCT 2018). The provision of energy includes many steps, such as the raw material extraction, material processing, transportation, distribution, consumption, etc. These processes are associated with release of the emissions which results in environmental impacts. There is a need to promote life cycle thinking to improve understanding about product impacts and to take more informed decisions. At this stage we are in the third generation of biofuels and must consider the environmental impacts and avoid the shifting of environmental impacts to other areas. In South Africa at the moment, there are an increased number of the biomethane production facilities across many different regions in the country. These biogas production system facilities utilize various waste-based residues for the production of biomethane. At the moment the "hydrogen economy" is receiving great attention for industrial applications.

In this light, there is a need the Life Cycle Assessment (LCA) method can play a critical role in decision support for policy through providing comprehensive assessment of the environmental impact of third-generation biofuels. However, nowadays priority is placed on the sustainability assessment of products. Sustainability and sustainable development are considered as important topics for world economies in the 21st century. The term "sustainability" came into the spotlight during the massive oil crisis that was experienced in the 1970s, and then the world governments started to seek solutions for resources and waste management. This led to the formation of the United Nations Commission on Sustainable

Development, known as the Brundtland Commission. The Brundtland Commission published a report titled “Our Common Future” in the year 1987. This commission defines sustainable development (SD) as the “development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs” (Brundtland 1987). Furthermore, sustainability can be regarded as the condition whereby a property of something is considered sustainable.

Over the years both the, United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) have worked together to develop life cycle-based methods to evaluate the sustainable development. In 2009, the UNEP/SETAC working group published guidelines for “Life Cycle Sustainability Assessment (LCSA)” to evaluate the holistic assessment of the three dimension of s (addressing environmental, economic and social aspects) of sustainability (Finkbeiner et al. 2010). By definition, the LCSA is known as the holistic approach to evaluate environment, social, and economic impacts of a product or services with the objective to a more sustainable production and consumption of product through their life cycle” (Finkbeiner et al. 2010).

The LCSA takes up the structure of sustainable development (SD) to a great extent. It takes the triple bottom line of sustainability by integrating life cycle assessment (LCA) to represent the environmental dimension, life cycle costing (LCC) to represent the economic dimension and social life cycle assessment (S-LCA) to represent the social dimension. At the moment, the evaluation of the LCSA methodological problem is still ongoing, as the lack of suitable procedures for objective measurement of quantitative S-LCA, has hindered the application of the LCSA method from being used on a wider scale. There is much work that needs to be done on the theoretical development of LCSA, and studies are currently underway to address several outstanding matters of LCSA. At this stage the priority is to develop methodological approaches for the sustainability assessment of processes, products, services, and technologies etc.

1.2. Problem statement

The recovery of energy in the form of methane-containing biogas through anaerobic digestion (AD), especially of organic wastes, is starting to receive significant industrial policy attention in South Africa. In light of growing demand for renewable transportation fuels also, it is unclear whether the transition from standard biomethane production to waste-based biohydrogen production would improve or worsen the environmental impacts and benefits. Indeed, little is known about the energy and environmental performance of waste-based biofuels in Africa, with only a few life cycle assessments (LCAs) so far published on African energy systems. The United Nations Environment Programme (UNEP) has long recommended the use of environmental LCA to support policy development also in developing countries, pertaining to sustainable consumption and production. More recently, the UNEP Life Cycle Initiative has started to recommend economically and socially extended analyses, under the new term "Life Cycle Sustainability Assessment" (LCSA). It is not known whether such analysis can be completed, in a developing country context for energy system development questions, such as the one which biogas derives from organic waste and for which purpose.

1.3. Objectives

1.3.1. Aim of the study

This study aims to use the Life Cycle Sustainability Assessment (LCSA) approach, as recommended by UNEP/SETAC Life Cycle Initiative (UNEP/SETAC 2009), to investigate next generation energy options to support green economies in Africa. Furthermore, this study also aims to provide useful insights for research and development for colleagues working on biotechnological fuel production and on energy policy pertaining to a "hydrogen economy" in developmental context as found in South Africa.

1.3.2 Specific objective of the study

The specific objective of this study is to generate a number of biomethane production and use scenarios for African urban, rural and agro-industrial settings, and to compare their life cycle environmental, economic and social performances to those of the biohydrogen alternative, using a life cycle sustainability assessment methodology. The comparison involves the system-wide energetic efficiencies of the conversion of the waste-carried energy into fuels (i.e. biomethane and biohydrogen) and further into power and heat using cogeneration systems to generate electricity and heat (i.e. gas engine or fuel cell systems), or transportation fuel in vehicles (i.e. compressed natural gas vehicles or fuel cell vehicles).

1.4. Overview of the thesis

The objectives of the study are listed in Chapter 1, while the research questions are listed and discussed in Chapter 3. Chapter 2 presents a detailed literature review which provides critical insights on the theoretical context of lifecycle-based methods for sustainability assessment of products, with special focus on the Life Cycle Sustainability Assessment (LCSA). The chapter explores writings on sustainable development and how the concept of life cycle sustainability assessment has evolved, pointing out the current status from a methodological point of view. Some knowledge gaps are identified through the review of previous studies. The motivation is to address gaps and develop solutions for African contexts to evaluate future energy infrastructural development. Chapter 3 starts by listing and discussing the research questions that are generated in this study in relation to the study objectives. The methodological approach for life cycle sustainability assessment involving the three dimension of sustainability is clearly articulated in Chapter 3. Chapter 4 provides the results of this study for each study case that is generated, and the end-application of fuels is: either for electricity generation or application as transport fuels. The results of life cycle sustainability assessment for each study setting is discussed in detail in the following chapters (Chapter 5, 6, 7). Chapter 5 presents the results and discussion for the Agro-industrial setting, Chapter 6 represents the results and discussion for the Urban setting, Chapter 7 those for the Rural setting. Chapter 8 provides the case comparison of the scenarios which are represented in Chapters 5, 6 and 7. Finally, Chapter 9 summarizes and provides recommendations and the conclusion of this study.

2. CHAPTER 2: LITERATURE REVIEW

This chapter is the literature review chapter and provides critical insights on life-cycle-based methods for sustainability assessment, in the context of the waste-based bioenergy technologies (specifically to make biomethane or biohydrogen). The chapter starts by focusing on the integrated assessment modeling frameworks to evaluate the social, environmental and economic dimensions of gaseous biofuels for application in electricity generation systems or as transport fuels. The Life Cycle Sustainability Assessment (LCSA) was developed in the main for the holistic assessment of the three dimension of sustainability, namely: the environmental, economic and social aspects. This chapter presents a review of the tool used to assess each of these three dimensions, the Life cycle assessment (LCA), Life cycle costing (LCC) and the Social-life cycle assessment (S-LCA).Thereafter the Life Cycle Sustainability Assessment (LCSA) is reviewed as the main proposed model for sustainability assessment. Finally, the identified research gaps are summarized and discussed in this section.

2.1. Gaseous biofuels production from waste-based residues

Biogas can be produced from a variety of waste-based residues such as municipal solid wastes, animal manure, sewage sludge, fruit and vegetable wastes, agriwastes, and various crops, etc. In most cases these waste-based residues are identified as low-cost feedstocks for biofuels production. The selection of feedstock for energy generation is a complex and requires a typology in terms of feedstock choice, feedstock collection and transport to biogas plant/landfill site. In certain instances the selection and use of a particular feedstock for energy generation might be uneconomical and detrimental to the environment. This is due to the fact that the collection and pre-treatment of feedstock for energy generation is done differently from one setting to the other. For example, feedstock are gathered or collected differently from one setting to the other setting, whereby others requires single point location while in others multiple points of locations for collection. In getting sufficient feedstock, it is important to keep in mind feedstock availability can be either abundantly available or limited in a particular geographical location. Therefore, the choice of waste-based residues for energy generation needs to be investigated in different locations in order to ensure selection of sustainable viable feedstock.

Matteo et al. (2017) concluded that energy harvesting from waste is a feasible option to handle the societal challenge to move towards more sustainable energy pathways. Their study highlighted how the urban context and its use could affect the opportunity to produce energy from waste or to convert it in fuel. At the moment the sustainability performance of utilizing different kinds of organic waste-based streams for energy generation in different African geographical regions is unknown. There are reports that certain organic waste-based residues for energy generation might not be sustainable and can actually result in more environmental pollution. Therefore, there is a need to determine the use of feedstock for energy generation in different geographical settings. The quality of the collected feedstock is affected by the way it is collected and careful consideration needs to be taken into account for the selection of feasible feedstock for bioenergy production.

The sustainability performance of the production and application of gaseous biofuels at different geographical regions is unknown. The choice of the location for the bioenergy production has the influence on the overall sustainability performance. Different geographical regions have different feedstock types, infrastructure development, access to services, human capacity, etc. Since the sustainability performance of bioenergy technologies not only depends on the bioprocess production but also considers these other important factors in order for the technology to efficient and operational. Therefore, it is important to understand and identify key stakeholders that play a key role towards the development of the biogas sector in a particular setting. These key role players play a crucial role in ensuring the development and success of the newly established biogas plant.

Dung Thi (2016) provided a comparison of electricity generation of food waste via anaerobic digestion versus dark fermentation from real study cases, reporting that anaerobic digestion (AD) could give the highest energy benefits, and is the most suitable method for the commercialization of food waste (FW) treatment, with 220 kWh/ton FW in comparison with the 12.5 kWh/ton FW. The inhibition of biohydrogen production might be due to increasing concentration of lactate, propionate, and valerate through the whole process. Clearly, the biohydrogen production process faces several challenges and suffers from the low productivities and yields. However, the application of biohydrogen either in either in electricity and vehicles operations brings considerate environmental benefits such as due to zero carbon emissions. Often, the focus is the electricity generation and it is therefore important to consider the comparison of biohydrogen application in electricity generation versus vehicle operation. Therefore, there is a need to determine the energy benefits that can be achieved from the use of different waste-based residues for either application in electricity generation or as fuels for the vehicles.

In terms of geographical settings, the urban areas are mostly populated geographical regions with high levels of the generation of the organic fraction of municipal solid waste (OFMSW). Therefore, it is important to consider the urban density and urban area to determine the role of the energy benefit of the waste-to-energy opportunity. Dung Thi (2016) reported that the use of organic fraction of municipal solid waste (OFMSW) in anaerobic digestion for electricity generation is believed to have high potential and economic benefits, while Stafford (2017) reported the use of biogas in transportation delivers more financial value-adding compared to using biogas in electricity. Manyuchi et al. (2017) investigated the techno-economic performance of the application of biomethane produced from OFMSW transportation vehicles. They reported that 29% of the investigated bus vehicles can be fuelled by the biomethane economically. They recommended that a 50-ton OFMSW/day plant production capacity promises higher returns on investment with a shorter payback period. There is a need to understand the potential benefits of the application of biomethane either in electricity generation or as vehicles for the fuels in terms of sustainability performance. There is a need to determine the potential of the use of waste-based residues in different regions for the production of energy. The potential benefits needs to be studied for different geographical regions as they have different kinds of waste-based resides.

2.2. Life cycle assessment (LCA)

The Life Cycle Assessment (LCA) is a technique for assessing the environmental aspects and potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (ISO 2006a and UNEP 2011). LCA studies the environmental aspects and potential impacts through a product's life (i.e. cradle-to-grave), which means the product or service is followed throughout every process, for example: feedstock generation and collection, pre-treatment, processing gas upgradation, fuel comprehension, fuel distribution and fuel end use. The environmental impacts include emissions to air, water and soil, waste and use of natural resources. A "positive environmental impact is the one that improves the environmental performance, or one that results to avoided environmental burdens", while on the other hand, a "negative impact is the one that causes or worsen the environmental performance". LCA is the only life cycle approach that has been approved by the International Standardization Organization (ISO standards). Generally, the ISO standards such as 14040 (ISO 2006a) and 14044 (ISO 2006b) provide principles and framework for life cycle assessment (LCA) including: 1) goal and scope of definition, 2) life cycle inventory (LCI) analysis, 3) life cycle impact assessment (LCIA), and 4) interpretation of the results, as seen in Figure 6.2.

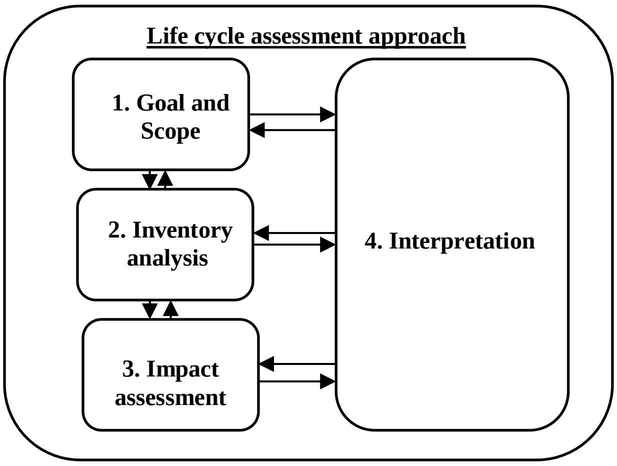

Figure 6.2: Life cycle assessment framework (ISO 2006a and ISO 2006b)

There are three different types of LCA. They are: i) Conceptual LCA – Life Cycle Thinking, ii) Simplified LCA; and iii) Detailed LCA. The different types can be used in different ways and have strengths and weaknesses, depending upon the context in which they are used. Life Cycle Assessment (LCA) typically does not address the economic or social aspects of a product. Over the past decade there has been a paradigm shift from "traditional" toward "modern" environmental protection approach. The modern approach takes into account sustainability ("triple bottom line") in an integrated processes and innovation -- see Table 2.2.

Table 2.2: Paradigm shift from “traditional” towards “modern” environmental protection approaches (adopted from Rubik 2002)

Characteristics	“TRADITIONAL” Environmental protection	“MODERN” Environmental protection
Political background	Control of risks, dangers	Sustainability (“triple bottom”)
Primary policy principle	Command and control	Push and pull
Main actor	governments	Society (“shared responsibility”)
Policy setting	confrontation	Cooperation
Principle for action	Local, national	Proactive
Regional scope	Production (“single processes”)	international
Focus	Single compartments and emissions	Products (“process networks)
Environment	Separate processes, end-of-pipe	Complete cross-media view over the complete life cycle
Environmental technology		Integrated processes, innovation

There has been a growing concern about continuous implementation of unsustainable biofuels. Nowadays, countries are currently developing standards and regulations to ensure that biofuels are indeed reducing greenhouse gas (GHG) emissions and promoting a sustainable development. Policies focusing solely on specific environment benefits, such as the reduction of fossil carbon emissions, may create surprises regarding overall sustainability. For example, Germany is recognized as one of the successful countries with the huge share of renewable footprint in their energy markets. When taking a closer inspection of biogas production in Germany, it has been reported that the economic incentives for the renewable energy production (Renewable Energy Sources Act) have increased biogas production, causing local conflict related to changing agricultural landscapes, increasing land prices and experienced loss of quality of life -- not only this, but the reception of renewable energy (particularly biogas) receiving criticism in relation to their ecological and socioeconomic sustainability. Nevertheless, these investigations analyse different aspects and there are still many open questions due to various assumptions, different biomass inputs, changing system boundaries and different conversion technologies in the other studies.

Over the years there have been efforts to find alternative renewable energy to drive industrial development to support the economies of countries. There are various types of renewable energy fuels that have been proposed in the past years to be considered for the energy generation. Singh et al. (2011) provided insightful literature of the third generation of biofuels, including liquids (i.e. bio-ethanol, biodiesel, and bio-methanol) and gaseous biofuels (i.e. biomethane and biohydrogen). This review paper show the potential of the renewable energy technologies for the generation of the future energy carriers. However, given the historical realities of the utilization of renewable energy fuels, it has been reported that some of the biofuels generation technologies could be very detrimental to the environment and unsustainable when compared to fossil fuels. Clearly, the development and implementation of unsustainable biofuels might actually contribute more to climate change than gasoline and diesel. Nowadays, there are various tools that have been developed by various research groups to investigate the sustainability development of the implementation renewable energy technologies. Hydrogen over the years has been promoted as the future energy carrier to drive industrial development. Hydrogen is regarded as an ideal fuel for future transportation because it can be converted to electric energy in fuel cells or burnt and converted to mechanical energy without obvious production of CO_2. Biological hydrogen production from biomass would provide an energy-saving, cost-effective and pollution-free alternative and should be investigated extensively based on these merits (Masilela 2011)

Most of biohydrogen research has been intensively focused on the bioprocess of conversion of biomass to make a suitable feedstock for production of biohydrogen. A lot of research attention has been given to the optimization of the dark fermentation process in terms of yield and rate of hydrogen production. Biohydrogen can be generated by adopting different technologies and different technologies can perform differently. The dark fermentation technology is reported to be technical feasibility and the large scale production and is not beyond reach (Ngoma et al. 2011 and Obazu et al. 2012). At the moment, the target for the production of biohydrogen production technology is 1-10 kg H_2/day by dark fermentation of biomass from a variety of waste-based residues.

Over the years, the life cycle assessment of the biohydrogen studies has been reported in literature, and some of the reported studies have been listed in Table 2.3. It is important to realize that many of these studies have different goals and scope, different functional unit, system boundaries and inventory data gathering approaches. Furthermore, many of these studies do not consider the entire composite of the biohydrogen production and application processes as envisioned in the society. For example, the system boundaries excluded the environmental impacts of the fuel end-use. By excluding the fuel end-use this will results to the omission of the environmental impacts related to the gas purification, gas storage and fuel application either electricity generation systems or as fuels for the vehicles.

Manish and Banerjee (2008) compared four different biohydrogen production processes (dark-fermentation, photo-fermentation, two-stage process and biocatalyzed electrolysis) utilizing sugarcane as feedstock. This biological processes were compared also with a base case method steam methane reforming (SMR) on the basis of net energy ratio, energy efficiency and greenhouse gas (GHG) emissions. Their study results showed that biohydrogen technologies results to lower energy efficiencies but have reduces greenhouse gas emissions when compared to steam methane reformation. Furthermore, they pointed out that energy efficiencies of the biological processes could be improved by ensuring by-products removal and utilization during the production process.

Wulf and Kaltschitt (2013) provided the life cycle assessment of biohydrogen production from biomass as a feedstock for the application of the fuel as a vehicle fuel. This study investigated the life cycle assessment of six different biohydrogen production pathways and assessment of the biomass potentials for the pathways. Their study highlighted which biohydrogen production pathways should be considered and also pointed out production pathways for biohydrogen that should be avoided. They further reported that biohydrogen production from energy crops should be avoided and biohydrogen production pathways that consume too much operating energy should be avoided. A study by Ochs et al. (2010) performed a LCA evaluation (cradle-to-gate) of a proposed plant for thermophilic production of biohydrogen using potato steam peels under the assumption of a complete substrate oxidation to produce only CO_2 and sewage as by-products. Their study revealed that the non-thermal small-scale decentralized hydrogen production shows a 5.7 times higher environmental impact that is larger than scale centralized steam methane reforming (SMR). The high inputs of chemicals such as phosphates and alkali especially produced from fossil fuels results to high environmental performance of the bioprocess. They pointed out areas of possible improvement of the technology that a recirculation of sewage would lead to an environmental impact that is only twice as high as large-scale SMR of natural gas. Clearly, the process of the biohydrogen production through dark fermentation still needs further improvement based on the outcome of the life cycle analysis, especially the cradle-to-grave analysis studies.

Djomo and Blumberga (2011) provided a comparative life cycle assessment of three different biohydrogen production pathways. The life cycle assessment was performed and compared the energetic and environmental performance of biohydrogen production from three different feedstocks (i.e. wheat straw, sweet sorghum stalks and steam potato peels. The three feedstocks had a different energy ratio and greenhouse gas emissions. They reported that careful consideration is needed when selecting the biohydrogen feedstock for energy generation. Furthermore, their study results indicated that biomass to hydrogen pathways reduce greenhouse gas (GHG) emissions by 52-56% compared to production of hydrogen (H_2) from diesel fuel and by 54-57% compared to steam methane reforming (SMR).

Table 2.3: A summary of studies reported on the life cycle assessment of biohydrogen production and application

Carbon source	Assessment methodology	Functional unity and inventory data	Environmental performance	Reference
SCJ	SimaPro v6	1 kg H_2, literature (laboratory experiments) and ecoinvent database	Biohydrogen production process is viable in net energy gain and GHG emission point of view. Reduce GHG emissions and non-renewable energy use by 57-73% and 65-79% when compared to SMR process.	(Manish and Banerjee 2008)
PSP	SimaPro v7.0, IMPACT 2002+	1 kg H_2 literature (laboratory experiments) and ecoinvent database	The two-stage process results in reduction of GHG, saving in the non-renewable energy resources and also human health impacts by a factor of two to three.	(Djomo et al. 2008)
PSP	SimaPro 7.1, Eco-indicator 99	1 kg H_2, laboratory experiments, ASPEN plus 2004.1 ecoinvent and BUWAL 250 database	The results were expressed in a points score (pts), and show that the two-stage fermentation process is 5.7 times higher compared to fossil based fuels (i..e. natural gas).	(Ochs et al. 2010)
WS, SSS and, PSP	SimaPro v7.1, IMPACT 2000+	1 MJ H_2, published literature, reports, ecoinvent and pilot plant input and outputs datasets	Different feedstocks resulted in different ER and GHG emissions. All the feedstocks showed a net positive energy gain. Two-stage biohydrogen process reduces GHG emission by 52-56% and 54-57% compared to diesel and steam methane reformation. (i.e. natural gas), respectively.	(Djomo and Blumberga 2011)
OFMSW	SimaPro ReCiPe	Annual capacity amount of OFMSW estimated at 18.000 tons. Ecoinvent database v 3.2	Three different scenarios for production of bio-methane were compared using Life Cycle Assessment methodology. The three upgrading processes are characterized by different impacts, showing in particular disadvantages in terms of energy demand and methane losses.	(Vignali and Vitale 2017)
Nutrient media	No clear methodology	No clear functional unit choice	The results of the analysis show that using biohydrogen to produce electricity offers more environmental benefits than using a fossil fuel based source. At this stage the positive result can be clearly seen in term of the climate change and human health categories.	(Romagnoli et al. 2011)
OFMSW	SimaPro v7.3, Eco-indicator 99 H/A	Production of sufficient fuel to achieve 1 km of passenger vehicle transportation. Ecoinvent database v.2.1	Based on the limited experimental data available two stage biohydrogen/biomethane production using food waste resulted in increased environmental burdens compared with the single stage process due to lower energy yields.	(Patterson et al. 2013)
Different kinds of feedstocks		1 kg H_2 production, Ecoinvent	This study provided the life cycle assessment of biohydrogen production from biomass as a feedstock for the application of the fuel as a vehicle fuel. It investigated the life cycle assessment of six different biohydrogen production pathways and assessment of the biomass potentials for the pathways. Their study highlighted which biohydrogen production pathways should be considered and also pointed out production pathways for biohydrogen that should be avoided. They further reported that biohydrogen production from energy crops should be avoided and biohydrogen production pathways that consume too much operating energy should be avoided	(Wulf and Kaltschitt 2013)
SCJ = sugarcane juice; PSP = potato steam peels; SSS = sweet sorghum stalk; WS = wheat straw; GHG = greenhouse gas; SMR = steam methane reforming; ER = energy ratio; H_2 = hydrogen.				

2.2.1. Goal and scope definition

Melamu and von Blottnitz (2009) highlighted that many of the LCAs studies on bio-energy technologies normally conduct the LCA in an attributional fashion – the type of LCA that allocates resources and pollution flows within a system to deliver a product or service, while, the "consequential" LCA attempts to explain how flows to and from the environment will change as a results of different decisions. Therefore, many of the LCA studies consider the consequential LCA because it addresses environmental consequences caused by technology or product selection change. The study goal depends on the objectives of the study and many of the summarized studies in Table 2.3 had been able to provide a clear study objective for the life cycle assessment of the biohydrogen technology.

After clear definition of the goal of the study the next step would be establishing a functional unit and the system boundary of the study. The selection of the functional unit is a very important step during the LCA: it is established in order to guide the reference flow of the consumption, emissions and products of the system. Among the LCAs studies there is no agreement on the type or kind of the functional unit that needs to be implemented for the measurement of the bio-energy technologies. It is important to emphasize that the functional unit differs from one study to the other as shown in Table 2.3. It is important to emphasize that the choice of the functional unit depends on the objective of the study which is eventually inform the systems boundaries that is developed in the study. At the moment, there is no consensus on the type or choice of functional unit to consider for the investigation of biofuel energy generation technologies.

The establishment of the system boundary is very important in the life cycle assessment stages. The system boundaries (SB) encompass all the processes necessary to deliver the system's functional unit. The definition of the SB then guides the selection of the processes to be taken into account (Jolliet et al. 2005). The system boundary considered in their study did not include the gas treatment and compression and storage process. They only considered the energy balance and greenhouse gas (GHG) emissions of the two-stage bioprocess fed with sugarcane.

2.2.2. Life cycle inventory (LCI) analysis

Life cycle inventory involves the collection and compilation of the data required to quantify all the relevant inputs and outputs associated with the production of the functional unit. The inventory analysis is a very crucial step for the LCA, include a detailed description of all environment inputs (material and energy flows) and outputs (air, water, solid emissions). The inventory data can be compiled from various sources using knowledge processes and various literature reviews. It can be based on the primary data (collected directly from primary plant) and secondary data (collected from literature and databases). Often the starting point is the construction of block flow analysis which reflects the major units of the processes. There are several studies that have reported on the LCA studies of both biomethane and biohydrogen studying the choice of impact categories (i.e. climate change, particulate matter formation, freshwater eutrophication, water depletion, and fossil depletion).

2.2.3. Life cycle impact assessment (LCIA) and interpretation

The life cycle impact assessment (LCIA) translates emissions and resource extractions into a limited number of environmental impact scores by means of so-called characterization factors. There are two mainstream ways to deliver characterization factors, i.e. at midpoint level and at endpoint level. Endpoint characterization factors, directly related to the areas of protection, were derived from midpoint characterization factors with a constant mid-to-endpoint factor per impact category. The LCIA phase quantifies the relative magnitude of all the environmental impacts by using several environmental indicators of which are built-in the LCA software tool known as SimaPro 7.1.

SimaPro is one of the commonly-used LCA software platforms which provides access to comprehensive life cycle inventory (LCI) database known as ecoinvent. The ecoinvent database provides a wide range of data which can be used for the simulations. For the simulation, the ecoinvent has methods developed in order to calculate the environmental burdens of products. The ReCiPe methodology is one of the ecoinvent method that can be used for the characterization of the environmental impacts (either at midpoint or endpoint level). The ReCiPe midpoint (E) methodology considers the following impact indicators, i.e. climate change human health, climate change ecosystem, fossil depletion, freshwater ecotoxicity, freshwater eutrophication, human toxicity, ionising radiation, metal depletion, ozone depletion, particulate matter formation, photochemical oxidant formation, terrestrial acidification, terrestrial ecotoxicity. These impact categories lead to three damages, namely: damage to human health, damage to ecosystem and damage to resources. Huijbregts et al. (2016) reported on the ReCiPe methodology that due to lack of data, the influence of time horizon and level of evidence was not considered in the characterization factors of for photochemical ozone formation, terrestrial acidification, freshwater eutrophication, land use and fossil resource scarcity. They further concluded that the ReCiPe2016 methodology provides a state-of-the-art method to convert life cycle inventories to a number of life cycle impact scores. They emphasized that the seventeen midpoint categories and three endpoint categories provide characterization factors that are representative on the global scale in line with the global nature of many products life cycles.

Djomo and Blumberga (2011) in their study compared 14 environmental impacts at mid-point level. However, their study noted the unavailability of data in some case and they concluded that the inclusion of new data might change the outcome of the performance. The performance of the life cycle performance largely depends on the quality of the inventory data used in the assessment. In most cases, many geographical regions where the life cycle analysis is undertaken, there are challenges of inventory data as most countries in the developing countries do not have mature databases. However, research efforts need to be undertaken to ensure that environmentally friendly production and consumptions is promoted even in the development countries using local geographical inventory data.

2.2.4. Life cycle interpretation phase

The LCA results are compared, and the comparison is based on the reference functional unit to compare the study scenarios. The results from the LCI and LCIA phase are interpreted to identify critical aspects, to evaluate alternative options. The interpretation of the life cycle assessment results requires dedicated approach to ensure that the results are relevant and accepted to the overall LCA community. Often the challenges with many life cycle assessment studies are the details of the revelation of the methodological approach and interpretation of the results approach. There needs to be clarity about the inventory data that is used in the study. There must be a well-defined structure for the impact assessment and presentation of the results for clear understanding of the study outcomes. Due to the complexity of the life cycle assessment often the results presentation is poorly presented and unclear about the outcome of the study.

2.3. Life cycle costing (LCC)

Life cycle costing (LCC) is a technique that can be used to capture all costs of a product or process across its entire life cycle (Hunkeler et al. 2008, UNEP 2011). For LCC, a SETAC "Code of Practice" is now available. Klöpffer (2008) pointed out that the LCC is a useful complement to LCA, and measure real monetary flows rather than focussing on the environmental impacts of a particular product. In 2010, Jørgensen questioned the relevance of life cycle costing (LCC) as one of the dimension of sustainability in the life cycle-based sustainability assessment (LCSA). They hold an opinion that the environmental and social aspects are sufficient for the determination of sustainability performance of products. While in the following year, Klöpffer and Ciroth (2011) published a paper which argue that sustainability has three dimensions: environment, economy, and social aspects in accordance with the well-accepted "three pillar interpretation" of sustainability. They stated that the LCC is an appropriate tool to be considered with the LCA and S-LCA, and allows the assessment of different actor perspectives such as real monetary flows of the products. However, they noted that LCC methodological needs some further research attention, and they suggested that case studies needs to be reported on the economic performance. Hall 2015 provided a review paper on the justification of the environmental life cycle costing as the economic pillar for life cycle sustainability assessment (LCSA). They pointed out the need to address the social costs, and they concluded that the life cycle costing provide a starting point for the global sustainability assessment in the future. Among, the three dimension of sustainability LCA is standardized while both the LCC and S-LCA are not standardized. There is a great need to bring the LCC methodological approach into maturity.

The penetration of hydrogen in the market requires its connection to energy prices in comparison with other fuels and end-use sectors (i.e. electricity use and mobility sectors). In terms of energy prices hydrogen per energy content is believed to be efficient. Mansilla (2012) assessed the market attractiveness for the penetration of hydrogen use as a fuel. Their study highlighted the need for economic instrument for the penetration of hydrogen in the market. They pointed out that several key players of hydrogen penetration might be its connection to the market price MJ and application (i.e. electricity generation or as fuels for vehicles). In earlier studies, the innovators of hydrogen considered the infrastructure availability (i.e. refuelling stations) as more critical than the technology price. However, nowadays the energy infrastructural development not only refers to the construction of the operational plant for hydrogen production but also considers the region readiness to implementation policy development and other regulatory framework (i.e. licensing, monitoring health and safety, etc.) for the renewable energy production technologies. Hay et al. (2013) reported that the economic analysis of the production of biohydrogen from waste-based residues is more expensive when compared to other fuels. However, they pointed out considering the pollution and factor for the environmental cost biohydrogen could become the preferred choice of fuel in the future.

Sen et al. (2008) provided the analysis of the biological hydrogen production and analysed the yields, reaction rates, reactor design and compared the effectiveness of the different substrate microorganism combinations. Their economic analysis study stated that operating cost is directly proportional to the hydrogen yield and capital cost or reactor cost is directly proportional to hydrogen production rate. This is a great concern, especially when biohydrogen production process is reported to have low production rates and yields at the moment. Not only is the biological process affected by the operational factors such as the production rates and yields of the process, but also by other factors such as the location of the digester plant. It is believed that a decentralized small-scale production facilities for biological hydrogen production could further reduce the cost.

Ljunggren and Zacchi (2010) evaluated an integrated process based on thermophilic and photofermentation with potato steam peel as substrate. They found that thermophilic fermentation process contributes 39% to the total capital cost and photofermentation was the major contributor to the operating cost. They also found that increasing the productivity by 100% there was a decrease of 33% in the capital cost contributed by thermophilic fermentation. On increasing the yields from 67 to 87%, there was a 7.5% decrease in total production cost. Researchers Das and Khanna (2013) pointed out that economic feasibility of dark fermentation will not be possible until biohydrogen yields reach 60–80%. Foglia et al. (2011) investigated dark fermentation followed by photofermentation. Their work compares the use of thermophilic fermentation and mesophilic fermentation in dark fermentation. The process was designed to produce 60 kg H_2 / h, which is equivalent to 2 MW thermal power. They had recirculated the effluent of thermophilic dark fermentation. This approach reduced the 60% of dilution water, which was required at the fermentation step without affecting system's yield and productivity. By the use of a heat exchanger, a large amount of heat was recovered during thermophilic fermentation, which had reduced the heat input required to warm the fermenter inlet to 70°C. They found that mesophilic fermentation required higher feedstock demand but lower heat input compared with thermophilic fermentation to produce the same amount of hydrogen. Although thermophilic fermentation showed lower productivities and therefore higher investment costs, but the authors expected better economic performance from the process when the feedstocks, like lignocellulosic waste, which requires pretreatment, are use.

2.3.1. Goal and scope definition

The first stage of the life cycle-based methods is to define the goal and scope of the study. Under the goal and scope of the study key aspects such as functional unit (FU) and the system boundary are addressed. The functional unit (FU) quantifies the function of product system and provide a reference unit. The choice of functional unit strongly affect the conclusion of the study (especially in comparative studies). Therefore, the choice of the functional unit must be defined in accordance with the goal of the study. The LCC should focus on the societal and economy wide impacts of the products system to reflect the value added to the society. However, when improving from micro- to macro-level (economic) assessment, LCC by its focus right now is not enough and still needs further research attention to include a set of indicators to cover the macroeconomic aspects of sustainability. Therefore, the environmental LCC can help consumers to make good decisions, and to point out the financial advantage of buying an environmentally preferable product. Clearly, there exists uncertainties about the focus of the LCC in terms of moving from micro- to macro-level (economic) assessment. Therefore, studies should be encouraged to report on the economic assessments that capture wider economic performance, not only production associated costs but also evaluate the economic contribution of the product to the society.

2.3.2. Inventory data analysis for LCC

The life cycle inventory stage is the approach towards the collection of the inventory data for the economic impact assessment. The inventory data to quantify the associated economic impacts can be obtained from various sources. It is time that countries or geographical regions starts to develop their own sets of inventory data to address their own sustainability challenges. Africa is expected to undergo through many infrastructural development and there is a need develop inventory database to address African challenges. The starting point would be to develop the input-output analysis (IO analysis) for the assessment of the economic performance of the infrastructural development in different geographical regions.

2.3.3. Economic impact assessment

The economic performance can consider a wide range of economic impacts. Often, impacts indicators are associated with the activity and are selected for a various number of reasons to achieve the purpose of the study. Essentially, financial flow data reflecting monetary flows can be presented for various sectors with economic indicators. This can be done through assessment of various sets of indicators such as direct cost (raw material cost, labour cost and capital cost), transport cost, application cost, financial costs (related to simple payback period (SPP), net present value (NPV), internal rate of return (IRR), etc.). The approach often involves real monetary flows covered by one or more actors in product system. It is important to realize that the biogas infrastructural development is largely dependent on the financial feasibility of installing the biogas digester in a particular geographical region. The life cycle costing considers various aspects of the economic performance such as installation costs of the digester, financial savings from fuel end use, etc. The evaluation for the life cycle costing of biogas infrastructural development is important because it informs the decision makers to invest in the biogas sector. The biogas sector consists of many key role players and their economic role across the cradle-to-grave perspective for biogas infrastructural development needs to be evaluated.

In terms of economic performance of the biofuels the life cycle costing is very important to reveal the performance of economic indicators such as contribution to Gross Domestic Product (GDP), employment, external cost, investment cost, income generated, local and foreign trade. Therefore, studies that report on the life cycle costing methodologies are encouraged in order to improve the maturity or understanding of the role of the LCC under the LCSA. Singh et al 2011 carried comparative study of the economics of different models of family size biogas plants for the state of Punjab in India. They calculated the payback period (PBP) for these model sized digesters. They found that different digesters have different payback period and net present values (for example the Deenbandhu model, of size 1 and 6 m^3, has a lower PBP of around 4.7 and 1.6 years than the janta model of the same size, PBP = 11.3 and 3.2 years respectively). The floating drum model of size 1 m^3 is found to have a high PBP of 26.6 years. Using the Lang factor (fL), Amigun and von Blottnitz also calculated the capital cost for different sizes of digesters. They found that an fL value of 2.63 and 1.79 years gives a better prediction of the capital cost for small/medium-scale and large-scale digesters, respectively (Amigun and von Blottnitz, 2010). It is important to realize that various economics models have been developed over recent years to predict the cost effectiveness as well as the costs and benefits involved in using biogas installations for domestic and local centralized biogas plants.

2.3.4. Interpretation of the economic indicators

Renewable energy technologies are believed to offer an alternative to partially replace or reduce our reliance on fossil fuels use for the energy generation. Therefore, it is important to determine the life cycle costing of these energy production systems in order to establish their economic viability. Goulding and Power (2013) reported that the end-use of biomethane as a fuel for compressed natural gas vehicles is economic feasible when compared to biogas application in combined heat and power systems (Goulding and Power 2013). Their study investigated three different types of feedstocks, namely grass silage, maize silage and barley silage and among these feedstocks grass silage outperformed the other feedstocks. It is very important to realize that every life cycle costing study is unique and depend on its own input-output analysis. Especially, the costing of products or processes is influence by many variable ranging from geographical location and economic status of the region or the country. Sometime the economic performance is influence by the inputs or the type of the technology that is employed for processing. Amigun et al. (2008) claimed that waste-based biofuels are cheaper from a life cycle perspective. Many studies have reported that growing the biomass feedstock incurred many economic and environmental burdens when compared to waste-based residues. Their study provided the methodological approach to estimate the capital cost of installing biodigesters in African settings (Amigun et al. 2008).

In South Africa, the installation of the biogas digesters is on the increase across different geographical locations, including the agro-industrial, urban and rural settings. Many of the family-sized biogas digester systems face several challenges related to biodigester construction costs, labour costs, feedstock availability, operation, and maintenance. It is important to realize that most of the installation of the biogas digester systems in agro-industrial and urban settings are financed most by private ownership. While, the installation of the biogas digester systems in rural areas is mostly subsidized by various stakeholders such as government and also funds donors. Therefore, there is a need to set up a viable financial model to support the biogas infrastructural development programmes across many (South) African regional contexts.

2.4. Social life cycle assessment (S-LCA)

In 2009, the UNEP/SETAC working group published a set of guidelines for Social-Life Cycle Assessment (S-LCA) for the evaluation of the social impacts (either positive or negative) of the particular product (UNEP 2009, Zamagni et al. 2011). S-LCA assesses the potential social impacts of products and relates to the different stakeholder groups affected by products, such as workers, local communities and consumers. The methodological approach towards the S-LCA is based on the common LCA approach referencing methodology based on ISO standards 14040 and 14044. Furthermore, the UNEP/SETAC working group published a methodological sheet which provides a framework and approach towards the identification and evaluation of impact indicators for the S-LCA (Ramirez and Petti 2011). The methodological sheets addresses, or classify the indicators and subcategories in relation to the stakeholder groups of the S-LCA methodology. Among the three dimension of sustainability, the social life cycle assessment (S-LCA) is the least developed and lacks scientific consensus on various aspects of the methodology. The approach towards the assessment of social impacts follows the standard LCA approach, which consists of the following four stages, namely: the definition of goal and scope of study, life cycle impact assessment, evaluation and interpretation of results. The overall methodological approach is presented in the guidelines for the assessment of the S-LCA as shown in Figure 7.2.

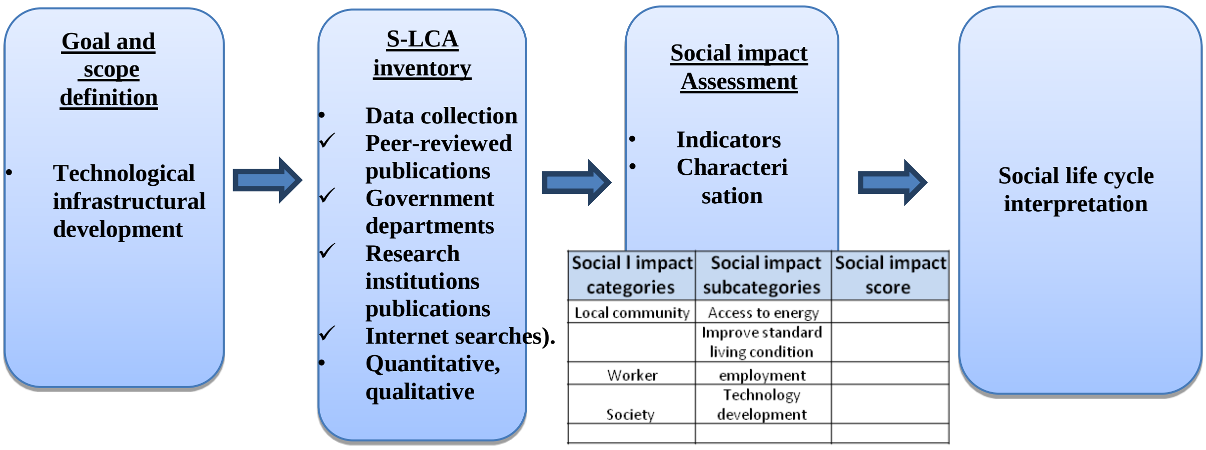

Figure 7.2: Approach towards social life cycle assessment of products (UNEP 2009)

2.4.1. The S-LCA goal and scope of this study

Concerning the S-LCA, the basic idea is that, social impacts assessment beyond the environmental assessment should be evaluated along the product life cycle. The S-LCA adopts a similar approach as the LCA; the goal and scope of the study becomes very important and determine the study focus and system boundaries that the study needs to consider. The functional unit is very important in every study, and should be carefully considered. Valdivia et al. (2013) reported that the LCSA is feasible for sustainability assessment of green economy products, but also reported major methodological challenges and practical assessment approach because the S-LCA is unclearly defined and still needs some further improvement in practice. Martnez-Blanco et al. (2014) opted to report the social effect rather than social impact in their LCSA study, stating the inability to calculate impact due to lack of relevant social impact indicators either positive or negative in their study. They concluded that S-LCA is still a young methodology facing many obstacles uncertainties to the extent of its application. Each dimension of sustainability (i.e. LCA, S-LCA and LCC) should have a sound relation in terms of functional unit, which allows the aggregation of the life cycle of a product, and LCA is used as a backbone for establishment of functional unit. However, Macombe et al. (2014) reported that the combination of S-LCA and LCA results may create some scientific problems. They opted that the multi-criteria decision analysis technique should provide a methodological framework for combination of S-LCA with LCA. Furthermore, they suggested that the role of the functional unit should be still clarified.

2.4.2. S-LCA inventory data analysis

During the life cycle stage the inventory data plays a crucial role in determining the quality of the study. The S-LCA is still very premature and often the identification and measurement of social indicators is very challenging at the moment. There is a various ways to obtain inventory data for the determination of the S-LCA. At the moment there existing databases either available on a top-down country or sector level for the evaluation of the S-LCA. The S-LCA faces serious challenges related to data gathering, even though a couple of S-LCA databases are in existence, for example Social Hotspots Database (Traverso et al. 2012). It is difficult to accumulate data, especially as most of these datasets can be obtained only from industrial companies – which is kept secret by most companies.

2.4.3. Social life impact assessment

In terms of life cycle-based methods the impact indicators generally represents a state of a certain aspect or effect that is measure or progress towards a stated goal. The impacts indicators functions as measured variables, parameters, but sometimes can function beyond measured values (Heink and Kowarik 2010). Over the years it has been observed that classifications of indicators is quite diverse; nonetheless indicators have been mostly described as an instrument to measure a causal effect. Finkbeiner (2006) reported on the social indicators and gave a total of over 150 proposed social indicators. Among these indicators, only a few can be directly assigned to products or processes. It is important to realize that some of the social indicators apply to specific regions/countries. As a consequence, a problem for an operationally feasible and applicability is not straight forward. It must be emphasized that using indicators of another reference level (organization, region) on another products system might raise methodological concern.

In recent years several different approaches towards social life cycle assessment (S-LCA) have been developed, and this has resulted to several impact categories being proposed (Weidema 2006, Jørgensen et al 2008, Benoit and Mazjin 2009), but they are lacking under the discussion, as the related impact pathways are lacking and the focus has been so far been on the representing of stakeholder groups without bridging the gap towards impact assessment. In general, the socio-economic impacts of the biofuel production and application are just as important as the environmental impact of the biofuels.

2.4.4. Interpretation of the social performance

Finkbeiner (2010) discussed that the weighting of social indicators faces major challenges. Other studies have proposed a couple of impact categories, but it must be mentioned that at the moment the relation between these impacts and their assessment pathway is lacking. The selection and quantification of the social indicators is still a challenge today. At the moment there is no usage of uniform standardized social sets of indicators. In order to set applicable and feasible indicator systems, it is important to develop a framework for the sustainable development indicator system (SDIs). Two distinctive main approaches have been proposed to develop a framework and select the SDIs. The approaches are often “expert-led” and “citizen-led” and are well documented in the literature.

There are three main indicator categories: a set of different indicators, indicator-based aggregates indices, and single-unit indices. A set of indicators refers to the indicator system that represents all the important aspects of sustainability. Indicator-based aggregate indices are structured by combining different indicators into an aggregated value by an arithmetic mean of different weights. The single-unit indices are often aimed to represent the relationship between the economic activities and the environment. The society involves three important sub-models, which are human health, employment, and public welfare. Public welfare is a function of income, health, education indexes, which indicates the human development index developed by United Nations Human Development Program (UN 2014). These indices are calculated based on the guides provided by United Nations, provided in the following subjection explaining public welfare.

Zamagni et al. (2011) pointed out the pros and cons of proposed guidelines for the S-LCA. They further stated that the methodological approach for S-LCA is not fully established and lacks consensual on number of issues including the identification of potential social impact indicators. Based on the literature review provided so far, the assessment of S-LCA in terms of methodological approach is not clear within the framework of LCSA. There is a great need to address functional units, system boundaries, selection of stakeholders, subcategories and indicators, aggregation, and impact assessment. However, there has been an interesting development regarding the implementation of stakeholders' analysis within the context of life cycle sustainability assessment (LCSA).

2.5. Life cycle sustainability assessment (LCSA)

The World Commission on Environment Development officially defined the term "sustainable development" (SD) as the development that meets the needs of the present generation without compromising the ability of the future generations to meet their needs (Brundtland 1987). Over the years the LCA's practitioners have proposed various life cycle methodologies for sustainability assessment. In 2010, the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (UNEP/SETAC life cycle initiative group) published guidelines for sustainability assessment, which is known as the "life cycle sustainability assessment (LCSA)" (Klöpffer 2008 and Finkbeiner et al. 2010).

$$LCSA = ELCA + LCC + S\text{-}LCA \quad \text{…………………….Equation 1}$$

The LCSA considers the evaluation of all environmental, economic and social impacts of the products throughout their life cycle. As seen in the above Equation 1, the LCSA is grounded in the “triple bottom line”, which takes into account the holistic assessment of environmental, economic and social aspects of a product. The relationship among the three dimension of sustainability is commonly portrayed as separate, hierarchy equal entities but holistically evaluated, as presented in Figure 8.2. Among the three dimension of sustainability the environmental dimension is quite well developed, and followed by the economic dimension. Unfortunately, the social dimension still needs further research to reach full maturity as compared to other two life cycle tools (i.e. LCA and LCC). It is important to highlight that every dimension of sustainability considered and evaluate different activities along the life cycle production of a particular product. Those different participating members can be considered as the stakeholders. Those participating stakeholders along the entire life cycle of production of a product must be synchronized in an integrated approach as presented in the LCSA.

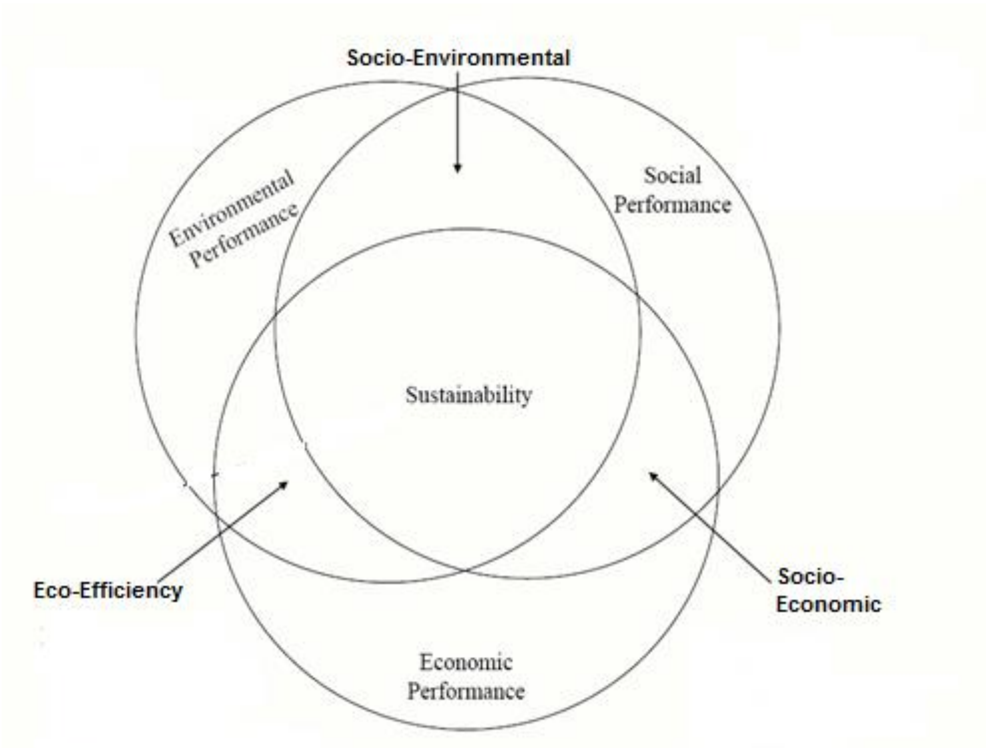

Figure 8.2: Three pillars of sustainability and their interconnections

Life Cycle Sustainability Management (LCSM) is the implementation of life cycle-based sustainability assessment of LCSA into real-world decision-making processes, be it on the product, process or organization level. In a nutshell, LCSM aims to minimize the environmental and socio-economic burdens associated with product or product portfolio throughout its entire life cycle and value chain. There has been some development in the field of life cycle sustainability management, for example Finkbeiner et al. (2010) presented an adaptation of Maslow's pyramid of human needs for a life cycle- based environmental and sustainability assessment approaches, see Figure 9.2. The adapted version starts with the basic approach of life cycle thinking, followed by single-issue methods like carbon or water footprint, life cycle assessment (LCA), resource or eco-efficiency up to life cycle sustainability assessment at the top of the pyramid (Finkbeiner et al., 2010).

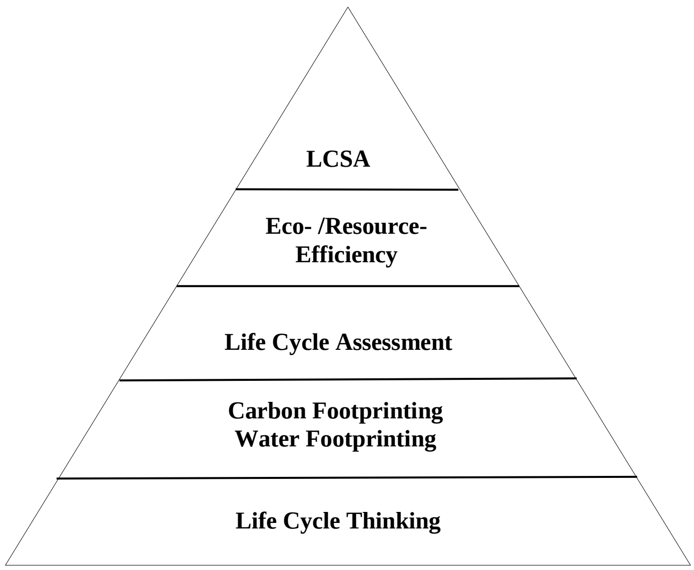

Figure 9.2: A hierarchy of life cycle based environmental and sustainability assessment approaches (Finkbeiner et al., 2010).

Life cycle thinking represents the basic concept of considering the whole product system life cycle from "cradle to the grave". It aims to prevent individual parts of the life cycle from being addressed in a way that just results in the environmental burden being shifted to another part. Life cycle thinking thus is a qualitative concept. With the next level in the pyramid the approaches start to be quantitative, including evaluation approaches for single environmental issues like carbon footprint and water footprint which have been receiving considerable research attention. The next level is presented by the life cycle assessment

(LCA), which aims to address all environmental impacts of a product or service, and does not involve the economic and social aspects. The next level is resource efficiency, which is an approach that combines the environmental indicators and economic dimension, but does not include the social aspect. On top of the pyramid is life cycle sustainability assessment (LCSA), which covers the three dimension of sustainability: the environmental, economic and social aspects of a product or service. The concept of LCSA is ultimately the way to go, and should be pursued in order to achieve reliable and robust results.

2.5.1. Approach towards life cycle sustainability assessment

There are several life cycle sustainability assessment (LCSA) studies have been reported in literature. As mentioned before, the UNEP/SETAC life cycle initiative published guidelines for sustainability assessment termed "life cycle sustainability assessment" in the year 2010. In the following year, Guinée et al. (2011) proposed a new life cycle sustainability analysis (LCSA analysis), which differs from life cycle sustainability assessment (LCSA assessment). They differ in terms of conceptual structure and modelling principles but both still shares the life cycle structure and some of the methods such as life cycle costing (LCC) and social life cycle assessment (S-LCA). According to the authors, LCSA (analysis) is able to accommodate knowledge from different disciplines relevant to sustainability and to better link questions to models of analysis towards trans-disciplinarily. The different disciplines are discussed in detail by Sala et al. (2013). It is able to accommodate knowledge from different disciplines relevant to sustainability and to better link questions to models of analysis towards trans-disciplinarily. Hu et al. (2013) presented the LCSA approach by putting the LCSA into practice by analysing the triple bottom line by life cycle implication of concrete recycling process. In another paper, Traverso et al. (2012) analysed the production steps of photovoltaic (PV) modules -- environmental, economic and social impacts of Italian and German polycrystalline silicon models are compared using LCSA.

2.5.2. Methodological approach for life cycle sustainability assessment

In terms of methodological approach, there is an issue of trade-offs between the three dimension of sustainability that still remains a challenge today. This is due to the fact that three different methodological approaches are considered with little or not enough understanding between the dimensions. Traverso et al. (2012) proposed presenting the results in a combined approach by introducing the life cycle sustainability dashboard (LCSD). This is an adaptation of Jesintghaus's (2000) dashboard of sustainability which was originally developed to assess and compare the economic, social and environmental factors in local communities. According to Traverso et al. (2012), the LCSD methodology has been proposed to compare sustainability performances of the same group of products as an effective supporting tool to present the rests in dissemination activities or decision-making processes in which expert stakeholders are usually involved. It must be emphasized that the proposed LCSA framework at theoretical and conceptual level lacked enough case studies prior to being proposed as the tool for sustainability assessment. A study by Neugebauer et al. (2015) developed the tiered approach, which seeks to offer direction of the model in terms of practicality, relevance and method robustness of the LCSA. The tiered approach seeks to offer the holistic assessment approach and pave a way towards single-dimension assessment.

2.5.3. Practical implementation of the life cycle sustainability assessment

Almost all case studies using LCSA focused on the "broadening of impacts" dimension rather than "broadening of system boundary" of analysis focusing on macro level impacts of production and consumption at the national and global economy level. The broadening of the stem boundary analysis through considering the production and application of biofuels is necessary. Obviously, with a globalization economy, while consumption of products takes in some parts of the world, manufacturing and consumption occurs in different parts of the world. Environmental burden shifting takes place and often resources from certain parts of the world are used for the production of products in other parts of the world. Therefore, sustainability studies needs to ensure accurate account of geographical resources, production and consumption in the particular geographical region. The importance of consideration of all indirect supply chain-related impacts (also called economy-wide macro-level analysis) within the LCSA framework is emphasized Guinée et al. (2011) as "inter-related global sustainability issues require more comprehensive approaches in which the macro-level impacts (economy-wide, or global) covering entire supply chain is essential to reveal sustainability impacts of products, services, or systems". Guinée et al. (2011) further emphasized the importance of IO analysis for the future of LCSA and discussed the necessity of a system-based sustainability assessment methods including hybrid LCA and IO LCA. Onat et al. (2014) presented a comprehensive macro-level sustainability assessment framework for alternative passenger vehicles in the U.S. Their study presents the input-output analysis and LCSA framework to evaluate the alternative passenger vehicles in the United States of America.

Onat et al. (2017) provided a review paper on the LCSA studies that have been reported in the past. They stated that according to their review paper, 40% LCSA studies are from the environmental discipline, while contribution from other disciplines such as economic and social sciences, and are very low, at 3% and 9% respectively. They stated that many of the studies are actually review papers, followed by qualitative papers. There is a significant representation of the quantitative data of the LCSA studies which are very important in capturing the impacts associated with the product, process or technology. Their review revealed that 46% of studies adopted scenario/policy assessment. Seventeen studies conducted uncertain analyses for their LCSA results and 38 studies applied multi-criteria decision making or stakeholder involvement in LCSA. On the other hand, only two studies utilized a complete system approach encompassing feedback mechanism and interconnections (indirect effect, the dynamic relationships among social, economic, and environmental dimensions, market mechanism, etc.). In terms of macro-level presentation they state that large-scale bioenergy production may affect the food supply, social structure (employed in different sectors), food prices, land use, and other indicators important to society, economy, and the environment. They conclude that the practical example of use of integrated LCSA methods and approaches are less studied.

2.6. Challenges of life cycle sustainability assessment of gaseous biofuels

Several studies have been reported to investigate the extent of the application and evaluation of LCSA in terms of methodological approach to investigate the sustainability of the products or services. However, there is a lack of scientific consensus on the LCSA methodology and the approach towards the integration of the three dimension of sustainability. Using the proposed sets of guidelines for the LCSA, there is no clear guide on the linkage or interaction among the three dimension of sustainability. Furthermore, Jørgensen (2013) discussed the definition of sustainability; his study questioned the assessment of the sustainable development within the context of the LCSA, elaborating that sustainable development definition is deeply rooted in the Brundtland definition of sustainability, therefore, the proposed methodological approach was not able to capture the entire breadth of the concept of sustainability. There is a question whether the entire sustainability performance can be captured within the context of the LCSA, or should be LCSA be broadened or not. It is clear that more LCSA studies are needed to understand the approach towards holistic assessment the three dimension of sustainability (i.e. environmental, economic and social). It is important to point out that among the three dimension of sustainability, only the scientific methodology for LCA is standardized. Clearly, this presents methodological challenges for the LCSA, and also provides an opportunity for further research and development for the LCA practitioners.

It is unclear whether the economic performance can be fully evaluated by using the life cycle costing. There is a concern that the economic indicators considered in the LCC are not enough to capture the economic performance at the global level. Guinée et al. (2011) reported that LCSA should broaden its scale from the product level to the macro-economic level due to the argument that no improvement in (macro) global sustainability may be achieved despite progress in micro sustainability of individual products and services. There are discussions whether LCSA should be broadened or not. This is in relation to the economic impacts indicators and at what level the LCSA should consider the economic indicators. A study by Hannouf and Assefa (2016) reported that the definition of sustainable development by the Brundtland report is actually understood exclusively to mean global macro-economic sustainability. They further stated that it remains to be seen how the targets play out when it comes to informing assessment of product level sustainability from a life cycle perspective. It is worth analysing the potential connection of the target to corresponding impacts associated with products systems. Clearly, the research is needed to advance the maturity of the LCSA, as most of the studies are reported at the micro-level to represent the sustainability performance of products or processes. A recent article by Steen and Palander (2016) interpreted the definition of the sustainability at macro-level, but with the aim of informing the focus of LCSA of product systems. The authors have proposed a change of structure of the LCSA to cover the general scope or definition of sustainability.

2.7. Summary of literature review and research gaps identified

The selection of feedstocks for energy generation is a complex process and requires careful consideration. In the case of life cycle assessment (LCA) of biomethane, some studies have been reported in literature, confirming that the biomethane technology offers potential benefits for the reduction of environmental burdens. For the biohydrogen production, on the other hand, the technology faces several potential bottlenecks in terms of productivities and yields. However, the research is ongoing and biohydrogen is reported to offer potential benefits in the future due to energetic value and zero emissions when used in combustion vehicles. The literature review shows that there exists no systematic guidance for the selection of potential feedstock for the gaseous biofuels production at different geographical locations. There is also a need to investigate the benefits of the production and application of gaseous biofuels in the particular geographical location. It is important to emphasize that successful installation of the particular technology depends on various key issues in a particular geographical location such as feedstock type, technology choice, access to services, human capacity, infrastructural development, etc. Furthermore, it is important to understand and identify key stakeholders that play a key role towards the development of the biogas sector in a particular geographical region.

There is a demand for LCSA studies which encompass the complete system approach showing interconnections among different dimension of sustainability (viz. environmental, economic and social aspects). At the moment there is a lack of universal consensus on the methodological approach towards life cycle sustainability assessment (LCSA); especially, there is no LCSA methodological approach for the comparison of the energy infrastructural development. To date, Life Cycle Assessment is the only internationally standardized methodology framework that can be used for environmental assessment of the product, process or service across its entire life cycle, for example “from cradle-to-grave”. This study considers the cradle-to-grave perspective because it takes into account the entire production and application of the products. This is relevant for sustainability: studies should define study goals that can assist towards achieving sustainable development goals. Every study has different study goals, but each of these must prioritize the assessment of sustainability of the entire production and end-use of the product.

The literature review clearly shows that no study has been reported on the LCSA performance of energy infrastructural development, specifically for cases of biohydrogen vs. biomethane energy generation technology. Further, there is little research on waste-based biohydrogen production in Africa compared to biomethane. The literature review indicates that there is no study that has investigated the sustainability performance of the infrastructural development of gaseous biofuels in African settings. Therefore, this is a chance for "first African LCSA study on gaseous biofuels", testing this tool as recommended by UNEP, by including social and costing angles. It is important to understand the extent of LCSA and its application for evaluation of sustainability assessment of renewable energy technologies, and to show the interconnections among the three dimension of sustainability in terms of burden shift within and between environmental, economic and social aspects.

In terms of methodological approach, there is an issue of trade-offs between the three dimension of sustainability that still remains a challenge today. This is due to the fact that three different methodological approaches are considered with little or insufficient understanding between the dimensions. Among the dimension of sustainability, social aspects have least been reported for gaseous biofuels production technologies. To the author's knowledge, so far no study has attempted to use the proposed Life Cycle Sustainability Assessment (LCSA) approach to evaluate the sustainability performance of the gaseous biofuels (biomethane and biohydrogen). Therefore, this study is very important to offer inventory data development and also methodological guidelines for assessment of sustainability implementation of energy infrastructural development in African settings.

Among the three life cycle tools, the life cycle assessment (LCA) is a matured life cycle tool when compared to the life cycle cost (LCC), while less focus has been given to the social life cycle assessment (S-LCA). It is unclear whether the economic performance of products can be fully captured by using the life cycle costing. There are concerns regarding the LCC that it might not fully capture the economic performance at both products level and global level. There are discussions whether LCSA should be broadened or not to accommodate economic impact indicators at global level. Clearly, the research is needed to advance the maturity of the LCSA for both dimensions in the economic and social aspects.

3. CHAPTER 3: RESEARCH QUESTIONS, APPROACH AND METHODS

3.1. Research questions

This section starts by stating the research questions of this study, as presented from section 3.1.1 to 3.1.5, while the study design and methodological approach are discussed in section 3.2. As mentioned in section 1.3, an objective of this study is to investigate the use of life cycle sustainability assessment (LCSA) for assessing next-generation energy infrastructure to support green economies in Africa. Therefore, this study considers the comparison of biomethane versus biohydrogen produced from three different organic waste streams (brewery wastewater, organic fraction of municipal solid waste, and cattle manure) and studies different applications, i.e. for fuel end-use in electricity generation (combined heat and power (CHP) systems, fuel cell (FC) systems) and for application as vehicle fuel (compresses natural gas (CNG) vehicles vs. fuel cell (FC) vehicles). The following research questions were formulated and investigated.

3.1.1. Which energetic yields can be achieved by biohydrogen relative to biomethane for typical feedstocks?

This study considers the utilization of three different feedstocks, viz. agro-industrial (exemplified by brewery wastewater), urban (OFMSW), and rural organic wastes (cattle manure). Based on the literature review on biogas yields (i.e. brewery wastewater, OFMSW, and cattle manure), biomethane achieves a significantly higher energetic yield than biohydrogen, at 9.00, 10.53 and 9.68 MJ/kg of VS. 4.78, 1.40 and 0.87 MJ/kg of VS, for the three substrates respectively. This difference in energetic yields significantly impacts on all further sustainability assessment, as the energy recovered from different wastes types. The biomethane production technology is robust and seems to be well suited for complex feedstock, as complex feedstock can be utilized in this process without requiring advanced pretreatment of the organic, while biohydrogen production technology requires complicated hydrogen infrastructure, and the issue of socio-technically support is very important to address the sustainability of the technology in a particular setting. In terms of sustainability, the implementation of a particular technology is not solely based on the production efficiencies and energetic yields of the particular process.

3.1.2. What are the comparative energy and environmental impacts of biomethane and biohydrogen?

Every considered waste-based residue results in different energetic yields for both cases of biohydrogen and biomethane fuels, and it is also assumed that the fuels will also likely have different energetic efficiencies in the application stage. A full comparison of the application of fuels is also considered, thus considering the end-application of the fuels (i.e. either for electricity generation or application in transportation vehicles).

3.1.3. How can biogas be used best to maximize resource efficiency and to enable sustainable development in different African settings (industrial, urban, and rural)?

The approach is to evaluate the entire energetic production and application of fuels, either for electricity generation or application as transport fuels. Therefore, this section not only addresses the environmental and energetic efficiency of the application of gaseous biofuels (i.e. biomethane and biohydrogen). But also covers all the life cycle sustainable tools as part of methodology in order to provide an approach towards the assessment of the three dimension of sustainability. The motivation is to provide an opportunity to perform the life cycle sustainability assessment (LCSA) of next generation energy infrastructure in Africa. Therefore, this study takes an approach of manipulating the current biomethane infrastructural development to instead produce biohydrogen. This is due to the fact that the biohydrogen as a fuel has advantageous fuel properties when compared to biomethane fuel.

3.1.4. What are the sustainability benefits and costs of introducing biohydrogen?

The LCA approach gives an opportunity for the environmental impacts assessment, but can be further coupled with LCC to calculate the economic aspect of the products or processes. Therefore, it is possible to evaluate simultaneously the environmental and financially preferred option between the biomethane and biohydrogen fuels. The economic aspect considers the entire value chain of a particular product. Sustainability by definition considers the production of products in a way that future generations will be able to meet their consumption needs. This study considers the cradle-to-grave perspective because it takes into account the entire production and application of the products. This is relevant for sustainability: studies should define study goals that can assist towards achieving sustainable development goals. Every study has different study goals, but each of these must prioritize the assessment of sustainability of the entire production and end-use of the product.

3.1.5. How can Social Life Cycle Assessment (S-LCA) be used within the context of Life Cycle Sustainability Assessment (LCSA) in energy technology assessments?

The life cycle sustainability assessment (LCSA) has been proposed as a tool for evaluation of sustainability which requires the evaluation of three dimension of sustainability, namely environmental, economic and social. This ensures that all dimension of sustainability along the life cycle-based modelling structure are taken into account to avoid issues in problem shifting. Based on the literature review provided so far, the assessment of S-LCA in terms of methodological approach is not clear within the framework of LCSA. For this reason, whilst the holistic way of the three dimension of sustainability is progressive, further broad practical correlation needs to be established between energy technology choice and the stakeholder groups. However, there have been interesting developments regarding the implementation of stakeholder's analysis within the context of LCSA, to accommodate some of the important social impact indicators is very crucial for the representation of the overall sustainability performance of the product, technology, or a service. After all, the social aspect considers the well-being of stakeholders of the introduction of new energy technology, and it is recommended that the multidisciplinary approach be developed in order to effectively evaluate the sustainability performance of products or technologies.

3.2. Study design and methodological approach

The first task of the study was to identify and select a suitable organic waste streams (i.e. brewery wastewater, organic fraction of municipal solid waste, and cattle manure) in each setting for the production and application of gaseous biomethane and biohydrogen. The study design is presented in Table 3.4, showing the designated study settings and the three fuel sources, for example: Agro-industrial setting (presented by brewery wastewater), Urban setting (presented by organic fraction of municipal solid waste), and Rural setting (presented by cattle manure). A total of six scenarios were generated, for a comparison of options of biomethane and biohydrogen production in different settings. Each scenario, in turn, considers two options for energy use, these being electricity generation or use in vehicles. Secondly, the methodological approach towards the integrated life cycle sustainability assessment (LCSA) framework is outlined in section 3.3.

Table 3.4: Study design showing the approach towards the comparison of life cycle sustainability assessment (LCSA) adopted in this study

Anaerobic digestion process (prod. biomethane)		Fermentation process (prod. biohydrogen)
Agro-Industrial: Brewery Wastewater		
• $LCA_{m,k}$		• $LCA_{m,k}$
• $LCC_{m,k}$		• $LCC_{m,k}$
• $S\text{-}LCA_{m,k}$		• $S\text{-}LCA_{m,k}$
• Integration ($LCSA_{m,k}$)		• Integration ($LCSA_{m,k}$)
Urban: Organic Fraction of Municipal Solid Waste (OFMSW)		
• $LCA_{m,k}$		• $LCA_{m,k}$
• $LCC_{m,k}$		• $LCC_{m,k}$
• $S\text{-}LCA_{m,k}$		• $S\text{-}LCA_{m,k}$
• Integration ($LCSA_{m,k}$)		• Integration ($LCSA_{m,k}$)
Rural: Cattle Manure		
• $LCA_{m,k}$		• $LCA_{m,k}$
• $LCC_{m,k}$		• $LCC_{m,k}$
• $S\text{-}LCA_{m,k}$		• $S\text{-}LCA_{m,k}$
• Integration ($LCSA_{m,k}$)		• Integration ($LCSA_{m,k}$)

Description of the coding for the study scenarios:

LCA: Life cycle assessment
LCC: Life cycle costing
S-LCA: Social-life cycle assessment
LCSA: Life cycle sustainability assessment
Set1: Setting 1 (i.e. brewery wastewater as a feedstock)
Set2: Setting 2 (i.e. organic fraction municipal solid waste as a feedstock)
Set3: Setting 3 (i.e. cattle manure as a feedstock)
[X]: Anaerobic digestion process (prod. biomethane)
[Y]: Fermentation process (prod. biohydrogen)
m: fuel application for electricity generation
k: fuel application for vehicle operation

3.3. Life cycle sustainability assessment (LCSA) approach

It is important to realize that the Life Cycle Sustainability Assessment (LCSA) approach builds on each of the three dimension of sustainability, i.e. environment, economic, and social aspects. The three dimension of sustainability can be modelled using the following life cycle tools: Life cycle assessment (LCA) evaluates the environmental aspect (section 3.4), and life cycle costing (LCC) examines the economic point of view (section 3.5), and Social-life cycle assessment (S-LCA) focuses on the social performance (section 3.6). These three life cycle tools are used as the sub-methodologies to represent the integrated life cycle sustainability assessment (LCSA) framework. Generally, the modelling phase of LCSA considers the following subsequent phases: 1) goal and scope of study, 2) life cycle inventory analysis, 3) life cycle impact assessment, 4) evaluation and interpretation of results. These stages are discussed in details in the following sections.

3.3.1. The goal of the study

3.3.1.1. The goal of the study

The goal of the study is to use the LCSA to compare biomethane versus biohydrogen produced from three different organic waste streams (brewery wastewater, organic fraction of municipal solid wastes (OFMSW), and cattle manure). The study boundaries include different application of fuels, i.e. for fuel end-use in electricity generation (combined heat and power (CHP) systems, fuel cell (FC) systems), and for application as vehicle fuel (compressed natural gas (CNG) vehicles vs. fuel cell (FC) vehicles).

3.3.1.2. Functional unit

The functional unit is defined as energy recovery from 1 kg volatile solid (VS) entering the bioprocess for each of the study scenarios generated in this study. Since the two different biotechnologies evaluated yield different products and different energetic yields, this comparative basis allow an assessment of which ultimately generates a better benefit to harm ratio from the available resource. The functional unit which is developed in the LCA is applied across all the other life cycle tools, including both the LCC and S-LCA. The bioprocess stages are shown in Figure 10.3, and the quantitative input and output data of the unit process are related to the defined functional unit of 1 kg volatile solid (VS) entering the system.

The selection of the functional unit is a very important step during the LCA because it provides a reference unit to guide the reference flow of the consumption, emissions and products of the system. The functional unit which is developed in the LCA is applied across all the other life cycle tools, including both the LCC and S-LCA. The inventory data for the three dimension of sustainability (i.e. LCA, LCC and S-LCA) was compiled based on stoichiometric calculations in relation to the functional unit.

The chosen functional unit in this study expresses all the functionality properties that are associated with the products or services. This means there is a causal relationship between the produced gaseous biofuels in MJ from 1 kg of volatile solids (VS) entering the system. For example “amount” of energetic fuel in MJ can be produced from 1 kg volatile solids (VS) during the anaerobic or fermentative digestion processes. The energetic products in MJ can either be used for electricity generation (kWh) or as fuels for the vehicles (km). It is also noteworthy that the functional unit here can be applied across different applications, i.e. use of energetic fuel (biomethane and biohydrogen) in electricity generation systems or as fuels for vehicles operations. The established functional unit is able to achieve comparability among different alternative scenarios generated in this study.

3.3.1.3. System boundary

The system boundary was developed and considers the approach considers all the life cycle stages for the production and application of gaseous biofuels (i.e. biomethane and biohydrogen technologies). The methodological approach involves selecting the impact indicators across the three dimension of sustainability in order to conduct the life cycle sustainability impact assessment (LCSIA). The LCSA results are presented as the sustainability performance index (SPI) for each scenarios developed in this study. For LCA, environmental flows are quantitatively related to the impact categories (either mid- or end-point) according to the environmental mechanisms, resulting in characterization factors for each environmental flow. The LCC is simpler, as economic costs and benefits are the only impacts that are taken into account. Regarding LCC impact categories, according to Swarr et al. (2011), “aggregate cost data provide a direct measure of impact and, thus, there is no comparable impact assessment step in LCC”. For the case of the S-LCA, it is recommended that categories be evaluated according to 31 subcategories as proposed by the United Nations Environment Programme (UNEP) and Society for Environmental Toxicology and Chemistry (SETAC). A methodological sheet was published for each of the 31 subcategories that can be used to assess the social aspects of products (UNEP 2013).

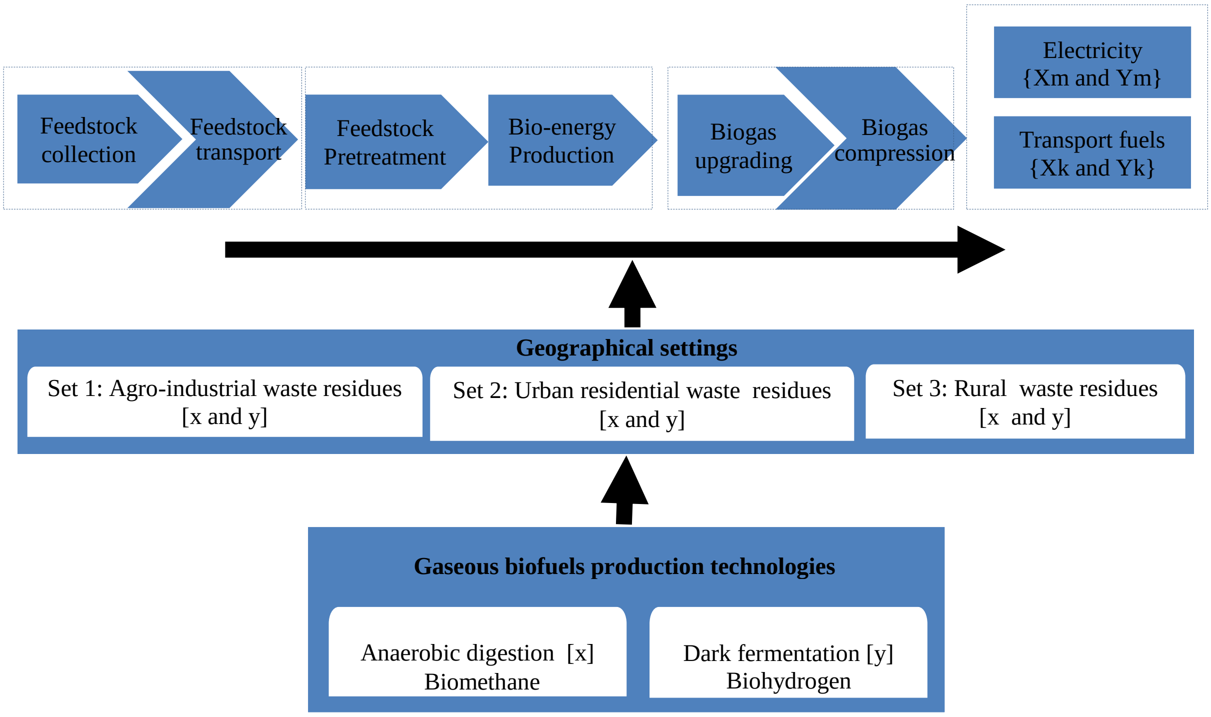

Figure 10.3: Life cycle stages of the production and application of gaseous biofuels

3.3.2. Life cycle sustainability inventory

The life cycle sustainability assessment (LCSA) is a system-based tool which deals with the evaluation of impacts associated with the environment, economic and social aspects. Each dimension of sustainability was modelled using the following life cycle tools: LCA evaluates the environmental aspect (section 3.4), and LCC examines the economic point of view (section 3.5), and S-LCA focuses on the social performance (section 3.6). Therefore, the approach towards data gathering and inventory analysis is extensively determined in every section in details.

3.3.3. Life cycle sustainability impact assessment

Figure 11.3 shows the framework approach towards life cycle sustainability performance, whereby the associated impact indicators are determined using the life cycle methodological tools. The framework is divided into three levels: Level 1 indicates the choice of impact indicators among the three dimension of sustainability. Level 2 shows the life cycle methodological tools for this study. Level 3 shows that after the inventory data gathering and characterization of the impacts indicators the results are organized to give the sustainability performance index (SPI) of the study scenarios.

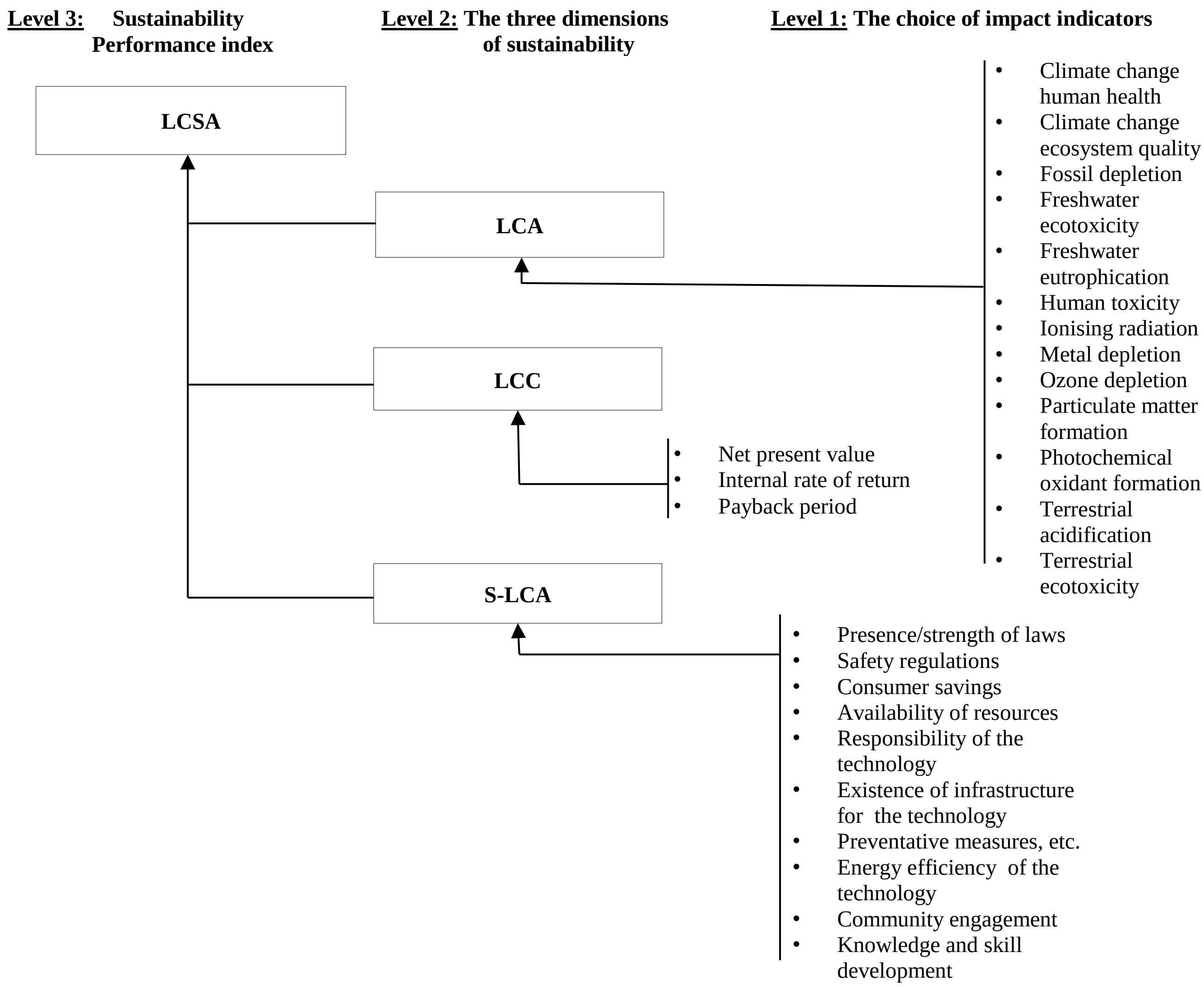

Figure 11.3: Approach towards life cycle sustainability assessment adopted in this study

In this study, it was specified that the three dimension of sustainability (i.e. environment, economic and social) have the same weight, but the indicators chosen have different percentages of contribution towards the overall sustainability performance. In order to relate them to a manageable and comparable number, the choice of indictors were classified as positive indicators and negative indicators. Negative indicators are those that high values have a negative contribution to sustainability (i.e. environmental indicators) and positive indicators are those that have a positive contribution to sustainability (i.e. economic and social indicators). Therefore, the weighting system was developed to transform the percentage values into score impact factors to present the overall sustainability performance index (SPI) value. The weighting system for scoring of impacts indicators for sustainability performance is presented in Appendix 11. In the case of the environmental indicators the score impact factor of 1 represent lower percentage contribution of 0.01-1.50%, i.e. 0.01-1.50% (1), 6.82-7.4% (0.75), 12.72-13.3% (0.50), 18.62-19.2% (0.25), and 22.16-22.74% (0.10). The score impact factors indicate better sustainability performance when the percentage values are lower. In the case of social and economic indicators, the score impact factor is defined as follows: 22.16-22.74% (1), 16.26-16.84% (0.75), 10.36-10.94% (0.50), 4.46-5.04% (0.25), and 0.01-1.50% (0.10). The score impact factors indicate better sustainability performance when the percentage values are higher.

In this study the weighting procedure of impact indicators for each dimension of sustainability (i.e. environment, economic and social) was undertaken in two ways in this study. Table 4.18 presents the results for the holistic integration of the three dimension of sustainability for all the study scenarios. The percentage results for the three dimension of sustainability were calculated and presented in Table 4.19. The weighting score factor was developed and presented in Appendix 11 which was used to score impact factors for all the three dimension of sustainability in order to present the single score, known as the sustainability performance index (SPI) value. The results for the sustainability performance index (SPI) values for all the study scenarios generated in this study are shown in Table 4.20. The presented sustainability performance index values indicate better sustainability when the values are higher.

The sensitivity analysis was carried out in order to determine the robustness of the life cycle sustainability assessment (LCSA) results obtained in this study. The sensitivity analysis involves generation of the alternative sustainability performance index (SPI) values that are obtained by changing key indicators parameters for each dimension of sustainability at 5%. In this study, it was assumed that the three dimension of sustainability, i.e., environmental, economic and social impacts, are equally important as recommended by UNEP/SETAC life cycle initiative. The results for the sensitivity analysis are shown in Appendices 12. The interpretation and discussion of the results for all the study scenarios generated in this study is provided in chapter 5, 6, 7 and 8. The discussion of conclusions and recommendations that are in line with the goal and scope of this study is discussed in chapter 9.

3.4. Life cycle assessment (LCA) approach

The environmental LCA components of the study were carried out using the LCA software tool SimaPro v7.1, and following the International Organization for Standardization (ISO) 14040 guidelines within SimaPro v7.1 Software. To date, Life Cycle Assessment is the only internationally standardized methodology framework that can be used for environmental assessment of the product, process or service across its entire life cycle, for example "from cradle-to-grave" (ISO 2006a,b). The LCA assessment approach consists of four steps: i) goal and scope of definition, ii) life cycle inventory (LCI) analysis, iii) life cycle impact assessment (LCIA), and iv) interpretation of the results. The goal and scope of the LCA are discussed and described in section 3.3.1, with some methodological notes on the inventory analysis and impact analysis steps given in sections 3.3.2 and 3.3.3, respectively. The results for the LCA modelling for all the study scenarios are presented in Chapter 4, and the interpretation and discussion of the environmental LCA results for the outcome of this study is done in chapter 5, 6, 7 and 8.

3.4.1. Goal and scope of the study

The life cycle assessment (LCA) aimed to determine and enumerate the environmental performance of the gaseous biofuels within the context of life cycle sustainability assessment (LCSA) as one of the dimension of sustainability. The LCA was used to compare the environmental impacts of biomethane and biohydrogen production and their final use in cogeneration unit systems to generate electricity or as transportation fuel in vehicles.

3.4.1.1. System boundary of the study

The system boundary (SB) encompasses all the processes necessary to deliver the system's functional unit. The definition of the system boundary then guides the selection of the processes to be taken into account. The system boundaries generated in this study are shown in Figures 12.3 and 13.3. The the system boundary is made up of the following unitary processes, namely: waste residue collection, transportation, pretreatment methods, bioconversion process (production of gaseous fuels), gas upgradation, compression and distribution and fuel end use (either for application in combine heat and power (CHP) or in fuel cell vehicles). The unit process stage of the system boundary is discussed in detail in the life cycle inventory analysis in section 3.4.2.

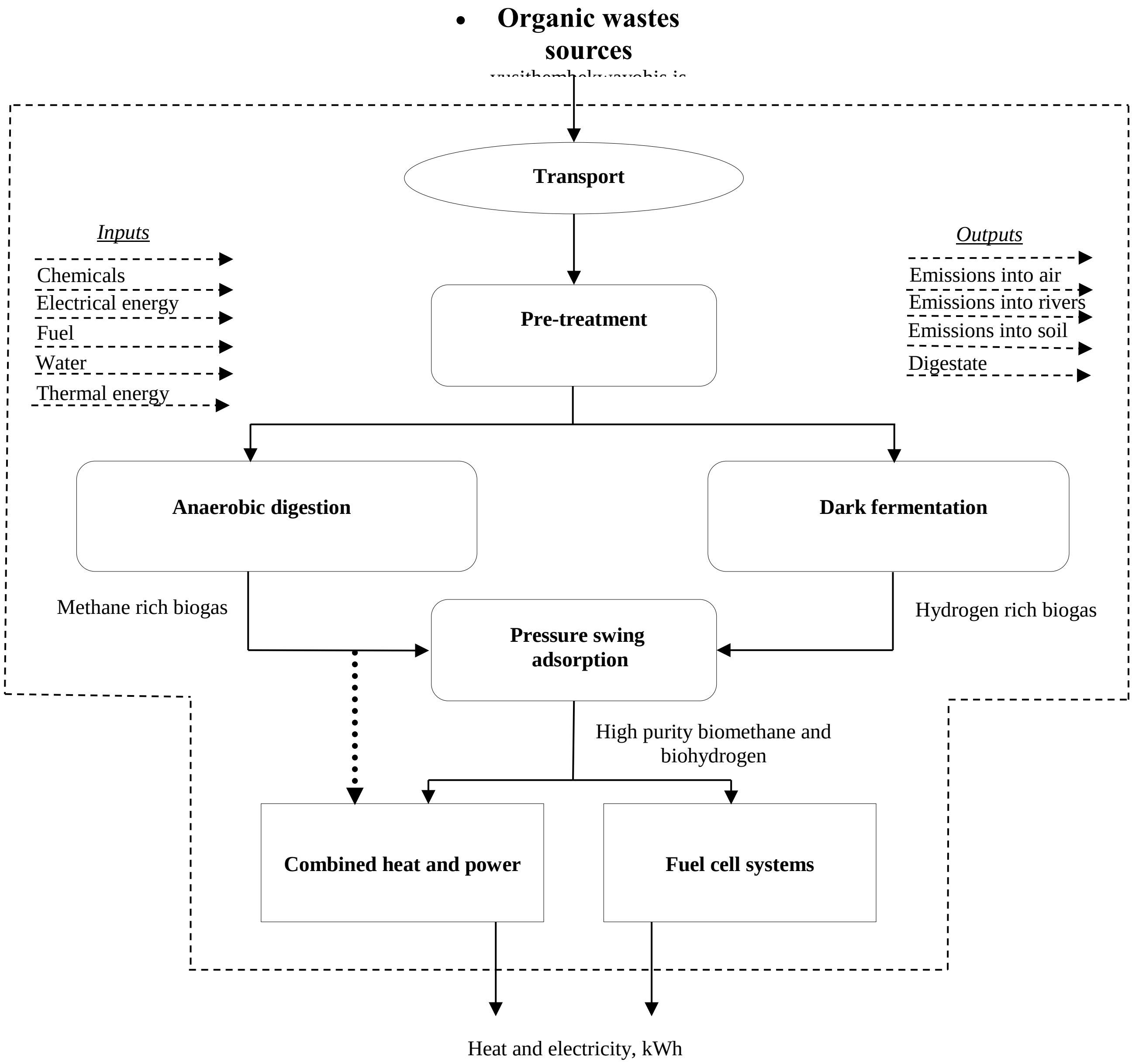

Figure 12.3: Flow chart showing a system boundary of the processes in LCA for electricity and heat generation. The dash arrows represent the flow of inputs and outputs from the system, solid black arrows represent direction of the flow from one step to another, while the solid dotted arrow represent the direct application of biogas without pre-treatment stage.

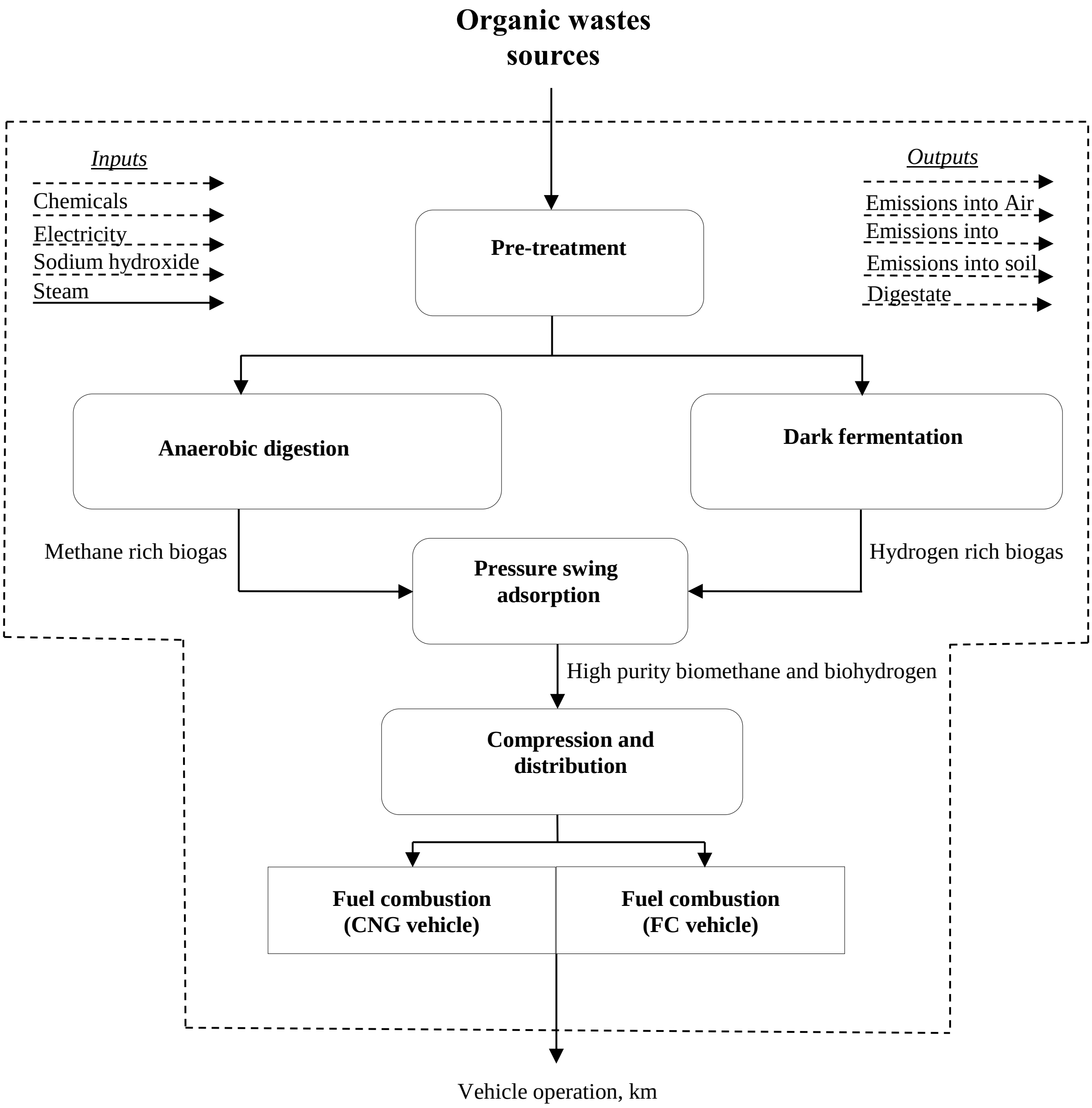

Figure 13.3 Flow chart showing a system boundary of the processes in LCA for vehicle operation. The dash arrows represent the flow of inputs and outputs from the system, black arrows represent the direction of the flow from one step to another.

3.4.2. Life cycle inventory (LCI) analysis

The cradle-to-grave analysis was taken into consideration and involved every stage across the production and application of the fuels. The following unit processes were identified across the entire life cycle performance of the fuels, namely: feedstock collection, feedstock pretreatment method, anaerobic digestion process, dark fermentation process, steam methane reformation, gas upgrading, compression and distribution, and fuel utilization stage. Each of the identified unitary stages was discussed in the system boundary section in 3.3.1.3. The inventory data for all the study scenarios is shown from Table 4.7 – 4.10 in chapter 4, showing the inputs (consumption of raw material and energy) and outputs (emissions and wastes as well as co-products) across the production and end-use of the fuels considered in this study. The inventory data was compiled based on stoichiometric calculations in relation to the functional unit. The life cycle inventory data was obtained from South African site-specific locations with digester installations. The approach towards inventory data collection from digester plants is described in the S-LCA section 3.6.1. In addition, the life cycle inventory data was also gathered from various source of literature and relevant publication sources (i.e. research publication papers, review papers, published thesis and research papers from various sources). The summary description of the unit processes considered in this study is provided below:

Brewery wastewater collection and pretreatment methods

South African Breweries Ltd (SAB) is a major brewing companies in South Africa operations in Newlands in Cape Town. A study visit was conducted to collect inventory data from the installed biogas digester plans in their facilities. Brewery wastewater comes from various procedures, such as the cleaning process of the malt production, brewing, bottling, and the wastewater from cleaning the recycled beer bottle and the packaging sterilization, as well as the overflow, disqualified product, and filter back wash water. This wastewater is rich in carbohydrates, pectin, mineral salts, cellulose, etc. Therefore, it is an organic wastewater with high biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD). Organic components in brewery effluent (expressed as COD) and is easily biodegradable as it consists mainly of sugars, soluble starch, ethanol, volatile fatty acids, etc.

The brewery wastewater leaving the brewery is collected in the conventional drainage system, where it flows to the contra shear pump. The contra shear pump drives the separation of solids and most of the suspensions contained in the brewery wastewater. The separated effluent is collected into the collection tank whereby the chemical dosing is done by injecting 1 M HCL and 1 M caustic soda (NaOH) to maintain the incoming effluent at desired pH level. Caustic soda is required to raise the pH of the feed or to increase the alkalinity. Hydrochloric acid is required to reduce the pH in the event that the feed becomes too alkaline and requires pH reduction. After the pretreatment stage the brewery wastewater is pumped into the digester for conversion bioprocess to take place. The values for the chemical inputs and outputs are presented as inventory data shown in Table 4.7 to 4.10. These tables show the life cycle inventory data which is generated for the study scenarios. The calculated values are based on the functional unit of 1 kg volatile solids (VS) entering the bioprocess.

Organic fraction of municipal solid waste collection and pretreatment methods

Organic fraction of municipal solid waste (OFMSW) produces one of the waste organic residues that is employed for biogas production in the anaerobic digestion process. The energetic value of organic fraction of municipal solid waste varies among different communities, but the heating energetic value of OFMSW is between 6 – 14 MJ/kg OFMSW, but an average of 9 MJ/kg OFMSW is often considered. OFMSW contains 29.7% TS and 69.3% humidity. Organic matter, as volatile solids (VS, contains 53% carbohydrates, 17% grease and oils, 15% is protein and 13% is lignin. As mentioned before, this study considered the organic input of 1 kg of volatile solids (VS) from OFMSW entering the bioprocess.

Communities in urban areas are experiencing high volume of OFMSW that often is directed to the landfill sites. The University of Cape Town installed the first biogas pilot project on one of its canteen premises. The digester uses separated organic waste (food scraps) from the Leo Marquard Hall Residence, and water is added to facilitate the decomposition in the biodigester in order to produce the biogas. The produced biogas is used to generate energy for the cooking purposes. The inventory data generation indicating the inputs and outputs values is shown from Table 4.7 to 4.10.

Furthermore, the inventory data for the OFMSW collection was obtained from the Wasteman Company, located in the Woodstock industrial area, Cape Town. Its core function is to offer waste collection service for the City of Cape Town, to collect household and city waste from suburbs of Cape Town. The collected waste material is transported to the landfill site for processing further. In this study the waste collection truck consume a diesel of about 0.0333 L/kg VS (OFMSW) collection. The company has documented information on their operations, and their database was used from log book operation. So, the company visits was conducted to collected inventory data on their operation through face-to-face interaction with one of the foreman operational officer of the company.

Cattle manure collection and pretreatment methods

Gawula, a rural village in the Greater Giyani area of Limpopo, consists of six (6) operating household scale biogas digesters providing the local community with energy for cooking and heating. The use of cattle manure is preferable for the local community, because of its abundance in the area. The cattle manure is collected and pre-treated, and the pre-treated sludge is fed into the digester. The inputs values for the pretreatment of the cattle manure are presented in the inventory shown in from Table 4.7 to 4.10.

Biomethane and biohydrogen production processes

After pretreatment of the organic wastes, the pretreated sludge is pumped into the Upflow Anaerobic Sludge Blanket (UASB) bioreactor for biogas generation. The microorganisms convert the organics in the sludge to produce biogas (methane rich gas), carbon dioxide and other by-products such as volatile fatty acids. The bioreactor is maintained at the operational temperature of 35 ºC, with supply of heat. However, the biomethane production process can be altered to produce biohydrogen instead under well-defined operational conditions. The anaerobic fluidized granular bed reactor (AFGBR) facilitates the simultaneous achievement of high hydrogen yields (HYs) and high hydrogen productivities (HPs). This prototype AFGB reactor uses anaerobic bacterial granules, thermophilic acidogenic bacteria and thermophilic volatile fatty acid (VFA) oxidizing syntrophic bacteria to produce biohydrogen, carbon dioxide and other traces of gases. The operational temperature for the thermophilic biohydrogen production process is maintained at

65 ºC, using either electricity or steam energy. The effluent digestate from the bioreactor is collected and transported to farms to use as manure fertilizer.

Gas separation/up-gradation

Pressure swing adsorption (PSA) can be used for the purification of gas products to obtain a highly purified gas for either use in electricity generation or as a fuel for vehicles. The PSA system can be designed to achieve up to 99.999 % purity (Mahler 2015), with the product recovery of between 50 % and over 95 %. The industrial unit system ranges from 100 Nm^3/h to 100 000 Nm^3 of output per hour.

Cogeneration in combined heat and power/fuel cell systems

The highly purified gas can be used to generate electricity in combined heat and power (CHP) or fuel cell (FC) systems, or else, the purified gas can be used as a fuel for vehicles. If the gas product is used as a fuel for vehicles, then the gas product after purification requires compression and distribution.

Vehicle operation

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET 1.7) model database developed by the U.S. Argonne National Laboratory has been used to compare fuel use and carbon emissions of hydrogen, methane and natural gas (Greenhouse gases, Regulated Emissions 2005). It computes total energy use, emissions of greenhouse gases (CO_2, CH_4 and N_2O), and emissions of six criteria pollutants: carbon monoxide (CO), volatile organic compounds (VOCs), nitrogen oxides (NO_x), sulphur oxides (SO_x), particulate matter with a diameter below 10 µm (PM10) and particulate matter with a diameter below 2:5 µm (PM2:5). The fuel life cycle consists of a fuel production stage, i.e., Well to Pump (WTP), and fuel utilization stage, i.e., Pump to Wheel (PTW). The WTP stage includes all activities up through fuel delivery to the filling station. The PTW stage includes all aspects of vehicle operation (combustion), but not vehicle manufacturing. The sum of WTP and PTW is the whole fuel cycle result, also called the Well to Wheels (WTW), which covers all stages of the fuel cycle, from energy feedstock recovery (well) to energy delivery as the vehicle (wheels). In this study, the system boundary covers the Well-to-Wheel (WTW) analysis of the fuel use for either electricity generation or as a fuel for vehicles.

3.4.3. Life cycle impact assessment (LCIA)

In this study, the impact assessment was performed using the ReCiPe midpoint (E) methodology. The following impact categories were characterized, namely: climate change, fossil depletion, freshwater ecotoxicity, freshwater eutrophication, human toxicity, ionizing radiation, metal depletion, ozone depletion, particulate matter formation, photochemical oxidant formation, and terrestrial acidification. The purpose of this study is to compare the infrastructural development of gaseous biofuels (i.e. biomethane and biohydrogen); therefore, it is the view of this research that the environmental impacts can either improve or worsen the environmental performance of the bioprocess technology. The chosen impact environmental indicators are justified below as recommended by ISO standard.

Climate change is a mid-point characterization factor which is widely used for global warming potential (GWP), which quantifies the integrated infrared radiative forcing increase of greenhouse gas (GHG), as express in kg CO_2-eq. Both the bioprocesses under the investigation and also the application phase of the fuels results to the emission of CO_2. Carbon dioxide (CO_2) is the main greenhouse gas, and 70-75% of all CO_2. Therefore, the CO_2 is considered to be the prominent global indicator for the impact emissions that results to climate change. The climate change impact on human health which effects the population through life expectancy. As transport activities increase, the related GHG emissions increases and accelerate climate change sharply. As the human health status changes due to GHG emissions resulting from passenger transportation, public welfare status changes accordingly.

Freshwater eutrophication (FEUT) is a serious environmental problem which results to the deterioration of water quality. It is a process whereby ecosystems or water bodies become enriched with chemical nutrients, typical compounds containing nitrogen, phosphorus, etc. The enrichment of water by nutrients has negative impact on the aquatic community and causes structural changes to the ecosystem. The biogas installations play a significant role in improving the sanitation and hygiene since the effluent wastewater from the digesters has less organic content which reduces environmental pollution.

Human toxicity potential (HTP) is the indicator that considers the characterization of toxic chemicals with relevant to human exposure. The emissions of some substances (such as heavy metals) can have impacts on human health. Therefore, human toxicity quantifies the emissions of these impacts in air, water, etc. The considered bioprocess does results in improving in reduction of the toxic chemical in the effluents of digestate from the bioreactor.

Freshwater ecotoxicity (FETP) is due to the emissions of metals to freshwater, and this includes nickel, beryllium, cobalt, vanadium, copper and barium, etc. The emission of some substances, such as heavy metals, can have impacts on the ecosystem. Assessment of toxicity has been based on maximum tolerable concentrations in water for ecosystems. Characterization factors are expressed using the reference unit, kg 1, 4-dichlorobenzene equivalent (1, 4-DB), and are measured separately for impacts of toxic substances.

Terrestrial acidification (TAP) is characterized by the changes in the soil chemical properties following the deposition of nutrients (namely, nitrogen and sulphur) in acidifying form. An area or regional ecosystem might be damaged due to cation leaching and this might have a detrimental environmental implication such as acid rain, etc. The bioprocess considered in this study are believed to improve the emissions into the environment, but actually results in release of effluent digestate that might be used as the organic fertilizers to improve soil condition.

Stratospheric ozone depletion (SODP) the ozone depleting potential (ODP) is expressed in kg CFC-11 equivalents (Chlorofluorocarbons-CFC's), and is a characterization factor on the midpoint level. When CFCs reach the upper atmosphere, they are exposed to ultraviolet rays, which cause them to break down into substances that include chlorine and bromide. The chlorine reacts with the oxygen atoms in ozone and rips apart ozone molecule. Ozone layer depletion has been pinned down to human activity, and the use of gaseous biofuels in this study has advantages to reduce the destruction of the ozone layer.

Ionizing radiation is the radiation that carries enough energy to pull electrons away from atoms. The atoms that have had electrons removed in this way are now charged particles, or ions, and hence the name "ionising radiation". The ionizing radiation is harmful and potentially lethal to ling beings. The collective dose resulting from the emission of radionuclide is the point where the characterization factor at midpoint level is derived. The midpoint characterization factor, called ionising radiation potential (IRP), is reported as Cobal-60 eq to air.

End-digestate as a fertilizer (EDF): the effluent digestate from the biogas digester operations can provide fertilizer that can be used for soil protection. The effluent from biogas digesters results in the provision of the organic fertilizer, in some instances depending on the type of feedstock used. The fertilizer improves soil structure and helps to reduce the use of chemical fertilizers which can be harmful to the ground water. In certain instances, the utilization of chemical fertilizers results in acid rain which is very harmful to the vegetation and also causes other environmental concerns.

Particulate matter formation potential (PMFP) is fine material that is dispersed in the air. The quality of air in the environment is usually measured for particles smaller than 10 micrometer (expressed as PM_{10}) or smaller than 2.5 micrometer (expressed as $PM_{2.5}$). There is a change in ambient concentration of $PM_{2.5}$ after the emission of a precursor, i.e. NH_3, NO_x, SO_2 and primary $PM_{2.5.}$

Photochemical ozone formation (POF) comprises secondary air pollutants which are formed in the atmosphere as a result of reactions between certain organic compounds such as hydrocarbons and nitrogen oxides. It is expresses in kg NOx-eq. The change in ambient concentration of ozone after the emission of a precursors such as nitrogen oxides (NO_x) or non-methane volatile organic compounds (NMVOC).

Metal depletion (MDP) is mostly used for the measurement of abiotic resource depletion which includes depletion of nonrenewable resources, for example fossil fuels, metals and minerals. The use of these resources beyond their rate of replacement is considered to be resource depletion.

Fossil depletion (FDP) is identified as underground nonrenewable energy fuels that are depleting. The use of non-renewable resources negatively impacts on the environment. Fossil resource depletion associated with electricity generation from hard coal. The South African electricity is mostly generated from hard coal, and this has serious detrimental environmental impacts.

3.4.4. Life cycle interpretation phase of the LCA results

This section describes the final phase of the life cycle assessment procedure. The interpretation of the results of life cycle inventory (LCI) and life cycle impact assessment (LCIA) are summarised and discussed as a basis for conclusions and recommendations in line with the goal and scope of the research, as recommended in ISO 14043. The life cycle assessment (LCA) was used to compare the environmental impacts of biomethane and biohydrogen production and their final use in cogeneration unit systems to generate electricity or as transportation fuel in vehicles. This study considers the comparison of biomethane versus biohydrogen produced from three different organic waste streams (brewery wastewater, organic fraction of municipal solid waste, and cattle manure). A total of 12 study scenarios were generated for the life cycle assessment, i.e. there are three electricity generation options from biomethane for each study setting, referred to as LCA:Set1:[X]m, LCA:Set2:[X]m and LCA:Set3:[X]m. There are two more options resulting from biohydrogen application in electricity generation, which are termed LCA:Set1:[Y]m, LCA:Set2:[Y]m and LCA:Set3:[Y]m. Another six options for application of both gaseous biofuels in transportation vehicles, for biomethane application in compressed natural gas vehicles (CNG vehicles) presented by LCA:Set1:[X]k, LCA:Set2:[X]k and LCA:Set3:[X]k and application of biohydrogen in fuel cell vehicles (FC vehicles) shown by LCA:Set1:[Y]k, LCA:Set2:[Y]k and LCA:Set3:[Y]k. The results of life cycle inventory (LCI) and life cycle impact assessment (LCIA) are summarised from Table 4.7 to 4.10 and 4.11 to 4.12, respectively.

The LCIA phase quantifies the relative magnitude of all the environmental impacts by using several environmental indicators of which are built-in the LCA software tool known as SimaPro 7.1. An LCIA was used within the LCA to compare the anaerobic digestion process (prod. biomethane) vs. fermentation process (prod. biohydrogen) for the option of the application of the gaseous biofuels in the electricity generation systems, and also in the transport vehicles, in order to obtain insights into environmental issues associated with the use of resources and emissions as gathered and compiled in the LCI. As discussed in section 3.4.3, the impact assessment was performed using the ReCiPe midpoint (E) methodology. The following impact categories were characterized, namely: climate change, fossil depletion, freshwater ecotoxicity, freshwater eutrophication, human toxicity, ionizing radiation, metal depletion, ozone depletion, particulate matter formation, photochemical oxidant formation, and terrestrial acidification.

The methodological approach for the compilation of the life cycle inventory (LCI) data is discussed in details in Section 3.4.2, and the LCI results for the environmental performance are presented in Table 4.7 and 4.10. Based on the LCI data presented in Table 4.7 to 4.10, the life cycle impact assessment (LCIA) results were generated within the context of LCA and are presented in Table 4.11 and 4.12. The normalization of the LCIA results was conducted by dividing each impact indicator by the sum of all impact indicators in every study scenarios generated in this study. Therefore, the environmental performance for each study setting is the sum of all the normalized values in percentage for all impact indicators as presented in Table 4.12. The normalized values range from 0 to 100%, and carries the weighting factor of 8.33. The normalized values indicate better environmental performance when they are lower. The environmental impacts for all the study cases was conducted for the comparison of the application of biomethane vs. biohydrogen in each and every study.

3.5. Life cycle costing (LCC) approach

The financial feasibility of the gaseous biofuel infrastructural development was analysed using the life cycle costing approach. As mentioned in the literature review, the approach towards LCC is similar to that of the LCA approach; it is important to mention that this study has only one goal and scope which is discussed in the LCSA section. This section discusses only the approach towards the life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation of the results. The methodological approach towards the life cycle inventory analysis and impact assessment is discussed in the following sections 3.5.1 and 3.5.2, respectively.

3.5.1. Life cycle inventory analysis

The life cycle inventory analysis requires collecting data for all process units. For each unit process all the flow rates for the inputs which made up the LCA inventory were multiplied by current prices, to get the costs and revenues for each unit process. Therefore, the LCC is as results of the aggregation of all costs which are directly linked to the production and application of gaseous biofuel in each setting. This is done by expressing financial cost from the input/output inventory data gathered from the LCA section. Total capital equipment costs is R30 000, and is distributed as follows: digester cost (R15 000), other materials (3 500), unskilled labour (R 6 250) and skilled labour (5 200). The life cycle costing considers the economic assessment of the infrastructural for the installation of the biogas system. The sets of indicators consider the installation of the biodigester systems, the application of the gaseous biofuels, the economic savings that are obtained by the installation of the biodigester system. In this study the life cycle economic perspective and the inventory data were gathered from various biodigester installations in different regions.

3.5.2. Evaluating the economic impact assessment

The life cycle costing assessed the benefit and cost of infrastructural development of the biogas project, by inspecting their ability to make profit from the perspective of investors. The following indicators were taken into account: the net present value (NPV) of the project was calculated, the internal rate of return (IRR) and the payback period. The NPV indicates whether the project is profitable (for example by taking into account the time value of the cash flows, i.e. revenue streams, capital investments and operational costs). It is defined as the difference between the present value of cash inflows and cash outflows. Therefore, if the NPV of a project is positive, the project should be accepted. Investments projects are often evaluated using the internal rate of return (IRR); it is the interest rate at which the NPV of all the cash flows (both positive and negative) from a project or investment is equal zero. In short, the IRR is the discount rate that produces a zero NPV. The project will be accepted if the IRR value of the project exceeds investor's required rate of return, otherwise the project should be rejected. To assess a new project's profitability, payback period is another vital determinant of whether to undertake the project. The payback period refers to the number of years it takes to generate enough revenue to pay the investment back, without taking into account the time value of money. Therefore, the payback period defines the time required to recover the investment capital and longer payback periods are typically undesirable for the investment. The following economic indicators were investigated:

***Net present value*:** The NPV indicates whether the project is profitable (for example by taking into account the time value of the cash flows, i.e. revenue streams, capital investments and operational costs). It is defined as the difference between the present value of cash inflows and cash outflows.

If the NPV of a project is positive, the project should be accepted. Therefore, this indicator provides an opportunity either to accept or to decline the implementation of a new energy infrastructural development.

Internal rate of return**:** Investments projects are often evaluated using the internal rate of return (IRR). It is the interest rate at which the NPV of all the cash flows (both positive and negative) from a project or investment is equal zero. In short, the IRR is the discount rate that produces a zero NPV. The project will be accepted if the IRR value of the project exceeds investor's required rate of return, otherwise the project should be rejected.

Payback period**:** To assess a new project's profitability, payback period is another vital determinant of whether to undertake the project. The payback period refers to the number of years it takes to generate enough revenues to pay the investment back, without taking into account the time value of money. Therefore, the payback period defines the time required to recover the investment capital and longer payback periods are typically undesirable for the investment.

3.5.3. The life cycle interpretation phase

The interpretation stage deals with the meaning and strength of the information obtained and processed from all the stages of life cycle phase. There are different ways of interpreting the results, depending on the kind of the study. The results for the economic performance of the production and application of gaseous biofuels are presented in Table 4.13. These economic performance results were then transformed into percentage ranging from 0 to 100% in Table 4.14. Therefore, the weighting system was developed to transform the percentage economic values into impact score factors to present the overall economic performance of the study scenarios, as presented in Table 4.15.

The developed weighting system for scoring of economic impacts indicators is presented in Appendix 10. In this study both the net present value (NPV) and internal rate of return (IRR) are classified as positive indicators, while the payback period (PBP) is described as the negative indicator. Positive indicators are those that have a positive contribution to sustainability performance (i.e. NPV and PBP) - their score impact factors indicate better sustainability performance when the percentage values are higher. While, negative indicators are those that high values have a negative contribution to sustainability performance (i.e. PBP) - their score impact factors indicate better sustainability performance when the percentage values are lower. In the case of the NPV and IRR the score impact factor of 1 represent higher percentage contribution of 22.16-22.74%, i.e. 22.16-22.74% (1.00), 16.26-16.84% (0.75), 10.36-10.94% (0.50), 4.46-5.04% (0.25), 0.01-1.50% (0.10). The score impact factors indicate better sustainability performance when the percentage values are higher. In the case of payback period, the score impact factor is defined as follows: 0.01-1.50% (1), 6.82-7.4% (0.75), 12.72-13.3% (0.50), 18.62-19.2% (0.25), and 22.16-22.74% (0.10). Table 4.15 indicate the economic impact results for all the study scenarios and the summed up overall economic performance value indicate better economic performance when they are higher.

3.6. Social life cycle assessment (S-LCA) approach

The social performance of the processes was analysed by using both the social life cycle assessment (UNEP 2009; Zamagni et al. 2011) and methodological sheet for social assessment (Ramirez and Petti 2011). The S-LCA provides the framework and methodological for social impact assessment, while the methodological Sheets define and classify the indicators and subcategories in relation to the stakeholder groups of the S-LCA methodology. This classification scheme is applied in S-LCA to ensure that the socioeconomic concerns of all impacted groups are taken into consideration. The approach towards the assessment of social impacts follows the standard LCA, consisting of the following four stages, namely: the definition of goal and scope of study, life cycle impact assessment, evaluation and interpretation of results. The goal and scope of the S-LCA are discussed in the LCSA section, and only the methodological approach of gathering data information and interpretation is presented in this section.

3.6.1. Life cycle inventory (LCI) analysis

In order to evaluate the social performance of the study, the data-gathering approach was done in two steps: the first part: 1). Digester plant visits were carried out to conduct case studies (to gather information via interviews, administering questionnaires, etc.); 2). A desktop literature search was carried to gather accurate information about the life cycle tools recommended for S-LCA. Firstly, the research ethics clearance was obtained to conduct these interviews from the University of Cape

Town, and the research ethics clearance topic discussed in details in section 3.6.1.1. Secondly, the inventory data gathering was conducted from various settings whereby the biogas digesters are installed and functional as discussed in section 3.6.1.2. Thirdly, some additional assumption were made by considering information collected through desktop literature search in order to obtain inventory data for the missing information as described in section 3.6.1.3. It must be noted that the inventory data was also gathered from well reputable sources published in literature, reports, and other scientific published reports, etc. The methodology of inventory data collection is described in the below sections.

3.6.1.1. Ethical issues

Firstly, the ethical clearance was sought and approved by the University of Cape Town ethics clearance committee before any data gathering was conducted. The ethics form is divided into two parts: Part 1 – the consent form (as presented in Appendix 7) and Part 2 – the questionnaire (as presented in Appendix 8). There are no ethical issues associated with the subject of the project, or implementation of the research findings from this study. The objectives, methodology and foreseen results have no ethical constraints whatsoever. In practice, the data gathering was conducted through Face-to-Face (i.e. interviews) on the specific sites where there is biogas digester installations. The method of data collection is through direct communication, whereby the interviewer explains the crucial information regarding about the background of the study and its objectives to the person who is being interviewed. The interview takes between 10 to 20 minutes.

3.6.1.2. Digester plants visits

Biogas projects in Mpfuneko community in Limpopo

Mpfuneko Community Support (CS) is a Non-profit and Public Benefit Organization operating in Gawula, a village in the Limpopo district of South Africa. The Mpfuneko biogas project is aimed at installing 50 digesters (Pasman 2004), however during the time of visit only six (6) digesters were in operation and others were still in the construction phase. The location of the active operational biogas digester plants is shown in Figure 14.3. These biogas digesters are installed within the household yard providing the occupants with the much needed biogas energy for cooking and heating purposes, as seen in Figure 15.3 and 16.3. In this way, households from these communities in rural areas can effectively produce their own energy needs. The local community participates in the construction, operation, and maintenance of these digesters. The installed biogas digester plants can provide work for the local community, income and various motivations (knowledge, skills and related agricultural activities). The use of organic wastes offers a variety of opportunities related to the economic and welfare of the local community. The use of cattle manure is preferable for the local community, because of its abundance in the area.

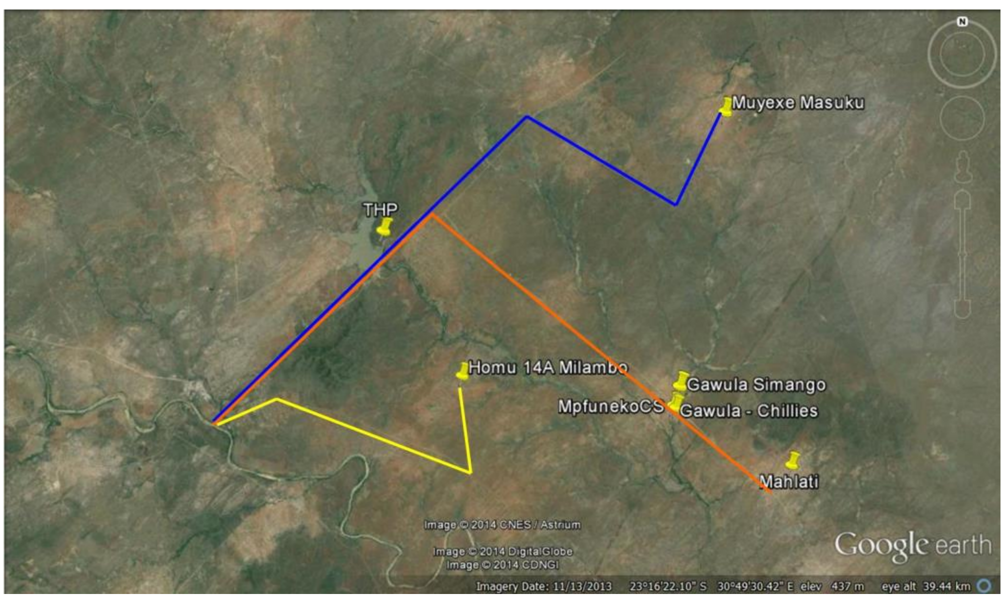

Figure 14.3: Google Earth map indicating the locations of the digesters in Gawula village situated in greater Giyani area of Limpopo province [Map -23.319288, 30.899649].

Figure 15.3: One of the installed operational biodigesters: A) collection and pre-treatment of the cattle manure; B) feeding the digester with pre-treated manure sludge; C and D) end use of the biogas as energy for cooking and heating water in the household.

Figure 16.3: Different stages of biogas digester construction

A field trip was undertaken for site-specific data-gathering from these biogas digesters to to investigate the economic value and social and environmental benefits of these digesters. The key focus of the research was to identify key barriers/challenges of currently operational biogas digester, and investigate whether the uptake of advanced technologies (such as biohydrogen technology) can be socio-technically supported in these settings. A questionnaire was administered, and the questionnaire template is shown in Appendix 8. It consists of two sections: section one (1) deals with inputs and outputs obtained by interview, and section (2) deals with the input and output data obtained through measurement of the digester performance. The datasets were obtained verbally and in writing, with operators of the digesters responding to the questions being asked. The questionnaire was analysed using both qualitative and quantitative methods.

With regard to evaluation of different form of feedstocks, this research is able to provide realistic consideration when dealing with energy transition, which is the case from biomethane to biohydrogen. The installed biogas digester plants can provide work for the local community, income and other various motivations such as knowledge generation, skills development and job opportunities, etc. The use of cattle manure offers a variety of opportunities related to the economic and welfare of the local community. Other opportunities come as a result of the implementation of the new energy infrastructural development in the rural settings. The installation of new energy infrastructural systems triggers new sets of opportunities for the local people.

Digester plant located at SA Breweries in Newlands

The South African Breweries (SAB) Limited is a major brewing company in South Africa. The company operates seven breweries and 42 depots in South Africa with an annual brewing capacity of 3.1 billion liters. SAB has set targets to reduce environmental impacts across the entire value chain of their operations. One way to achieve these targets is through installing the biogas digester plant in certain sites of their operations. For example, the SAB branch located in Newlands has installed a biogas digester plant which treats the brewery wastewater to produce the biogas. The biogas is used in combined heat and power systems to produce electrical energy and heat energy. The installed biodigester system is operated by skilled and experienced engineers who are currently employed on full time basis to work on the production sites. The installed biodigester system in the agro-industrial settings provides an opportunity for key fuel supply either for electricity generation or fuels for vehicles operations. The biogas could be compressed, in the same way common gas is compressed to compressed natural gas (CNG) and used to power vehicles.

Digester plant located at Leo Marquand Hall Residents at University of Cape Town

Due to high urbanization cities around the country are experiencing high volume of municipal solid wastes (MSW), and cities are unable to deal with the amount of waste. The first pilot project is based on the UCT premises whereby the anaerobic digester was installed by AGAMA Energy Company. The digester uses organic fraction of municipal solid waste (food wastes) from the Leo Marquard Hall Residence. The produced biogas is channelled and used for cooking purposes in the in the canteen of the Leo Marquard Hall Residence. The inventory data for the urban setting is obtained from both the digester located at the Leo Marquard Hall Residence and also from the waste collection company called Wasteman Company. The Wasteman Company is located in the Woodstock industrial area, Cape Town, and its core function is to offer waste collection service for the City of Cape Town, to collect household and city waste from suburbs of Cape Town. The collected waste material is transported to the landfill site for processing further. The company has documented information on their operations, and their database was used from log book operation. So, the company visits was conducted to collected inventory data on their operation through face-to-face interaction with one of the foreman operational officer of the company.

3.6.1.3. Selected data collection from literature review and other publications

The biogas sector is currently increasing in (South-) Africa with a numerous installations of biogas digesters systems in different geographical locations. It is unclear what drives the implementation of the renewable energy project in African regions, but there has been increasing in a number of developmental of commercial biogas projects across the country. However, there is no clear driving force between different stakeholders that drives the implementation of biogas projects. Therefore, there are no clear trade-offs between different stakeholder groups playing a role in the biogas sector in South Africa. The story of implementation of biogas projects has been a story of vision and perseverance from project developers who are willing to investment in the biogas projects. It is important to establish impact indicators that drive the implementation of the biogas projects. The government is committed to policy development, but there is a need to understand the demand and application of gaseous biofuel. The government plays a crucial role through policy development to support the implementation of the biogas projects. There are also various stakeholders within the biogas industry in South Africa that play a supporting role in the implementation of the biogas projects.

The social impact indicators capture all the success and hurdles of the implementation of the biogas projects that have gone ahead (or not) because of availability or absent of suitable policy development. The status of the policy development is important in order to establish the clear policy environment and regulations for the biogas projects, while it is important to understand that biofuels or bioenergy project are driven through government investment or policies, while others are driven through investment from private funders. The biogas industry is growing in South Africa, and some of the inventory data for the social life cycle assessment was obtained from various stakeholder groups (as presented in Appendix 9). Appendices 5 and 6 provide the list of research academic institutions that does research on topic of biomethane technology in the past five years in South Africa.

3.6.2. Social life cycle impact assessment (LCIA)

The methodological sheets provide a scientific approach towards selection of stakeholder groups, subcategories, and specific subcategory of assessment, etc. In total, the framework includes four stakeholder groups and 31 assessment subcategories. Table 3.5 a list of social impact indicators that were chosen in this study, namely: availability of resources, community engagement, knowledge and skill development, safe and healthy living conditions, consumer savings, and responsibility of the technology, existence of infrastructure for the technology, health and safety regulations, and energy efficiency of the technology. The Methodological Sheets place the social impact indicators into a stakeholder-based life cycle assessment framework.

This assists in the selection of social impact indicators and evaluating the causal effects between the social indictor and the stakeholder groups. Finally, the choice of selecting every social impact indicator is discussed in this section.

Table 3.5: Selected social impact indicators for this study

Impact categories	Impact subcategories	Criteria	Stakeholders
Cultural heritage	Acceptance of the technology	• Availability of resources • Community engagement • Knowledge and skill development • Safe and healthy living conditions (Preventative measures, emergency, protocols regarding safety measures, etc.)	Local community
Social economic repercussion	Contribution to economic development/technology development	• Consumer savings • Responsibility of the technology • Existence of infrastructure for the technology	Society
Working conditions	Health and safety	• Health and Safety regulations	Workers
Social benefits	End of life responsibility	• Energy efficiency of the technology	Consumers

Availability of resources: The South African energy system is mainly provided through centralized infrastructure, whereby abundant and fossil fuels used for energy production. However, the government is now slowly introducing new policies for the transforming into decentralized energy system. The decentralized approach provides an opportunity for the implementation of the technology outside the industrial realm and can be translated in society. Therefore, the implementation of biogas technologies follows the decentralized approach whereby the technology can be implemented based on the needs of the user, and/or resource availability.

Community engagement: The term "community engagement" is generally preferred to "participation" and points to the idea of partnership and shared responsibility. Building an operational partnership with the community, with the goal of improving relations between the communities for the technology acceptance. Both formal and informal partnership can be established to clearly define the roles and responsibilities of all partners: what each partner can contribute to the common goal. Each partner, alone, may not be able to achieve the goal without the synergistic contribution of the other. It is important to ensure that various stakeholder engagements in the communities are properly consulted and form part of the decision making process about the choice of the implementation of the new energy infrastructural development.

***Consumer savings*:** The installation of renewable energy technologies is believed to attract investment from local and international investors. This presents local communities with opportunities such as job creation and skills development during both the installation and construction of the projects. The installation of the biogas technologies can present an opportunity for various savings (i.e. savings on alternative fuel, the sale of digestate (fertilizers), annual cost of savings from water recycle (treated wastewater) etc.). This is due to the fact that the produced biogas provide the much needed fuel in the form of electricity or as transportation fuels.

***Health and safety regulation*:** Government is one of the key role players in the biogas sector. However, the government (as embodied by the executive, legislature, judicial, administrative, regulatory, and law enforcement organs) cannot effectively govern the natural resources without scientific input or societal consent and cooperation. Therefore, not only this is the responsibility of the government but also communities and also private sector. Companies have advance professional capacity to implement relevant health and safety regulation programmes such as occupational health and safety, business integrity, labour standards, etc. Therefore, the implementation of biogas technologies should be promoted towards meeting health and safety as required by the relevant authorities. A number of South African government departments are responsible for licensing and approval of renewable generation energy projects. Some of these departments include the Department of Energy (DoE), Department of Environmental Affairs (DEA), Department of Forestry, Fisheries and Agriculture (DAFF), National Energy Regulator of South Africa (NERSA), etc. The entire operations and activities of renewable energy projects require agreements and licenses, for example, the electricity generated can be sold to Eskom, municipalities, and/or private customer (off-grid taker) under government subsidy scheme (Independent power producer (IPP) procurement programme) by means of a wheeling agreements. Wheeling agreements need a memorandum of understanding between the partners involved. Other partnerships are lodged during early stages of the project development. For example, the participation of investors and project developers is crucial for the success of the renewable energy projects. It has been shown that government can gain a great deal by partnering with research institution/scientists and other members of the society (the public, NGOs, civil societies) in solving the societal problem. Every stakeholder has responsibilities, the government ought to provide regulatory and security services, while scientific institutions have the responsibility of fashioning out solution and serving in advisory capacity to both government and society. The private sector and NGOs (as part of society), in many cases, also provide infrastructural services for their employees and communities in the areas in which they operate. They could also serve as conduits through which government educates and communicates its policies on water, sanitation, and energy to the larger society.

Safe and healthy living conditions: The health of a community is a shared responsibility of all its members. Although the roles of many community members are not within the traditional domain of "health activities," each has an effect on and a stake in community's health. When designing, installing and maintaining the bioenergy infrastructural development it is important to consider the safety issues such as electrocution, gas explosion and asphyxiation, injury from fire, structural collapse. The new energy infrastructural development should be able to reduce the spread of diseases, including diarrhoeal disease, respiratory disease, injuries etc. There is a need to develop programmes that undertake preventive measures and action that promote health for communities in their own homes.

***Existence of infrastructure for the technology*:** Often in many regions there is a lack of necessary infrastructure facilities to support biogas implantation. Government must provide with equitable and atmosphere that promote investment and encouraging investors to play a crucial role in developing the biogas sector.

***Responsibility for the technology*:** Engineering ethics codes should be developed, improved, and operationally implemented during the technology development stages. There is a need to develop ethics codes that establish responsibility in relation to the use of the technology. The technology choice has ability to shape values, norm and culture of the society. Therefore. It is important to realise that technology must not advance only economic growth, but create ‘right livelihoods’. In order to establish ‘right livelihoods’ it is important to implement technologies that will be understood and managed by those who use them.

***Knowledge engagement*:** Social perception is a strong factor in the implementation of any policy, technology or idea, etc. No matter how rational the scientific recommendation, society perception may make its implementation difficult or even impossible. Society has always been the custodian of natural resources and could offer its opinion when sought. This opinion when acted upon by organized science becomes useful piece of information. The education and training partnership offer an opportunity for people to take interest in developing and installation of the biogas technology for energy generation. This might have a great impact to reduce the organic material being disposed in the landfills, and resulting in energy savings. The private sector through various social responsible programmes can install these digesters for the local community as a way of ploughing back to our communities. This type of partnership can drive effective change that moves our communities towards sustainable energy efficiency.

***Energy efficiency of the technology*:** It is important to understand the needs of the market by engaging in the deepest levels with the market. The market is the fuel end-users. In urban areas, people are changing and becoming conscious of energy efficiencies and the need to employ smart renewable technologies.

3.6.3. Social impact interpretation phase

The Social Life Cycle Assessment (S-LCA) was used to assess the potential social impact for the production and application of gaseous biofuels (i.e. biomethane vs. biohydrogen). The social impact is described as the influence of the energy system in the generation of social change and the associated human responses to those changes. The implementation of biogas infrastructural development for gaseous biofuel production can influence social change in the communities, fuel end users, project developers, policies, etc. Therefore, the ultimate consequence of a social impact experience is felt by the person (the human response), and this social change was investigated by conducting the interviews using the developed questionnaire as discussed in details in section 3.6.1.1.

Table 3.5 provides a set of social impacts indicators that were investigated in this study through the application of the methodological sheets for social life cycle assessment. After the set of indicators were determined, qualitative and quantitative data was collected from the site-specific locations where the biodigesters are installed as discussed in details in section 3.6.1.1. The questionnaire was administered to obtain qualitative and quantitative information about the production and application of gaseous biofuels. Both the qualitative and quantitative data was obtained as the primary socially life cycle inventory data that is effective to determine the “damages/impacts/area of protection” in relation to the production and application of the biofuels. The inventory data for the social impact assessment was obtained from site-specific inventory data (representing both the qualitative and quantitative data) whereby the biogas digesters are installed. Additionally, the inventory data was also obtained from various stakeholder groups as presented in Appendix 9.

In general, LCA and LCC use quantitative data, but the S-LCA might involve both the quantitative and qualitative datasets. The selection of functional unit is very important because in this study it provides a guiding link for the evaluation of impacts across the three dimension of sustainability (i.e. environmental, economic and social). The collected information across the three dimension of sustainability was therefore collected based on the same functional unit. The qualitative life cycle inventory data was obtained and subjected to the numerical verbal judgement approach, which involves transforming the transcribed qualitative data into quantitative by assigning impact scores. A simple numerical verbal judgement approach was used to score and aggregate social impacts scores in this study as presented in Table 3.6. The site-specific qualitative life cycle inventory data was assigned the appropriate score in relation to the five impact levels that are presented (i.e. very good, good, satisfactory, inadequate and poor).

Table 3.6: Numerical verbal judgement for assessing the social criteria

Five impact levels	Assign score	Assign factor rating
Very good	1	1.0
Good	2	0.9
Satisfactory	3	0.7
Inadequate	4	0.5
Poor	5	0.3

The numerical verbal judgement using the five impact levels was used to determine the outcome of a judgement in relation to how much one object is preferred over another, or whether it exhibits significantly different properties compared to another. Therefore, through the numerical verbal judgment the social life cycle inventory data was obtained and presented in Table 4.16 for all the study scenarios generated in this study. Table 4.17 present the internally normalized social impact performance results which were obtained by diving each social indicator value by the average sum of all the impact indicators for every study scenarios. The social impact assessment results indicate better sustainability performance when they are higher for all the study scenarios generated in this study.

3.7 Summary and Outlook

This study focuses on three different settings (i.e. agro-industrial, urban, and rural organic wastes), and these organic wastes have different energy yields during the biogas production process. Therefore, it is imperative to the energetic efficiencies of application of these organic feedstocks for useful energy source production. This study also emphasizes that the choice of a particular feedstock is not only based on the efficiencies, but also on the infrastructural development of that particular setting. The energy saving is experienced during the application phase of the produced gaseous biofuels. The application of the gaseous biofuel produced can replace a particular fuel which might have been produced from fossil based resources. The end-application of the fuels (i.e. either in electricity generation systems or application of fuels as transportation fuels in vehicles) has both energetic and environmental saving opportunities when replacing a fossil based fuel. The application of the gaseous biofuel in a particular setting is based on a number of factors such as the efficiency, infrastructural development, and the availability of resources to support the technology in the particular setting. For this reason, the evaluation of sustainability assessment requires the overall holistic assessment approach which takes into account the three dimension of sustainability.

There is a great need to evaluate the entire energetic performance, not just the end application phase of the fuel. Energetic efficiency encounters the entire energy use and product recorded along the supply and production chain of a particular product. The decision to implement a particular fuel must be decided on the basis of both the production energetic efficiencies and also the application stages of the fuel. It must be emphasized that the energetic efficiency is not only based on the end fuel application but the overall production and supply chain of the fuel. It is important to implement economic sensible technologies, and the life cycle costing (LCC) tool effectively calculates the economic aspect of the products or processes. The application of a particular technology depends on the economic vibrancy of that particular region. Therefore, the economic implications of the production and the application of needs to be understood. The life cycle sustainability assessment (LCSA) has been proposed as a tool for evaluation of sustainability, and the approach involves environment, economic, social dimension. Among the dimension of sustainability, the social aspect is the least developed among the three dimension and its application within the context of LCSA is poorly understood.

In the remainder of the thesis, Chapter 4 provides the results of this study for each study case that is generated. The results of life cycle sustainability assessment for each study setting are discussed in detail in the following chapters 5, 6, and 7. Chapter 5 represents the results and discussion for the Agro-industrial setting, Chapter 6 those for the Urban setting, and Chapter 7 those for the Rural setting. Chapter 8 provides the case comparison represented in Chapters 5, 6 and 7. Finally, Chapter 9 summarizes and provides recommendations and the conclusion of this study.

4. CHAPTER 4: RESULTS FOR ALL THE STUDY SETTINGS

This chapter provides the results for each setting and all the study scenarios that are under the investigation in this study. Chapter 4 is divided into four sub-sections. Firstly, section 4.1 provides the results for the life cycle assessment (LCA) of the three study settings which are under the investigation in this study. Secondly, section 4.2 lists all the results for the life cycle costing (LCC) of all the study settings generated in this study. Thirdly, section 4.3 provides the results for the social-life cycle assessment (S-LCA) for all the study settings, and finally, section 4.4 provides the results for the life cycle sustainability assessment (LCSA) for all the study setting and their scenarios.

4.1. Life cycle assessment (LCA) results

The life cycle assessment (LCA) was carried out using the methodology for the environmental assessment discussed in details in section 3.4. The methodological approach for the compilation of the life cycle inventory (LCI) data is discussed in details in Section 3.4.2. Based on the LCI data presented in Table 4.7 to 4.10, the life cycle impact assessment (LCIA) results were generated within the context of LCA and are presented in Table 4.11 and 4.12. The methodological approach for the gathering of the LCIA data and the interpretation of the LCA results is discussed in details in section 3.4.3 and 3.4.4, respectively.

Table 4.7: Life cycle inventory data for electricity generation from biomethane produced from three different organic wastes

Inputs	**LCA:Set1: $[X]_m$**	**LCA:Set2: $[X]_m$**	**LCA:Set3: $[X]_m$**
Feedstock:			
Volatile solids (kg/kg VS)	1.00	1.00	1.00
Nutrients:			
$CaCl_2$ * 2 H_2O, (kg/kg VS)	0.010	0.00	0.00
$CuSO_4$, (kg/kg VS)	0.00025	0.00	0.00
$FeSO_4$, (kg/kg VS)	0.00075	0.0000012	0.00
$MgCl_2$, (kg/kg VS)	0.00075	0.00	0.00
K_2HPO4, (kg/kg VS)	0.033	0.00	0.00
$CoCl_2$ x 6 H_2O, (kg/kg VS)	0.0000062	0.00	0.00
Resources:			
Water (kg/kg VS)	0.00	1.79	10.00
Diesel (L/kg VS)	0.00	0.033	0.0068
Hydrochloric acid (kg/kg VS)	0.036	0.00	0.00
Sodium hydroxide (kg/kg VS)	0.036	0.00	0.00
Energy:			
Electrical energy (MJ/kg VS)	0.47	0.54	0.34
Output			
Effluents:			
Volatile solids (kg/kg VS)	0.0081	0.33	0.18
Phosphate (kg/kg VS)	0.000028	0.00	0.00
Nitrogen (kg/kg VS)	0.000040	0.00	0.037
Ammonia, as NH_3-N (kg/kg VS)	0.00	0.00	0.00
Sodium hydroxide, (kg/kg VS)	0.00	0.00	0.00
Gases:			
Carbon dioxide (kg/kg VS)	0.19	0.26	0.21
Carbon monoxide (kg/kg VS)	0.0010	0.00068	0.00055
Benzene (kg/kg VS)	0.00	0.00068	0.00
Formaldehyde (kg/kg VS)	0.000066	0.0000045	0.000037
Methane (kg/kg VS)	0.0046	0.0032	0.0026
Nitrogen oxides, NO_x as NO_2 (kg/kg VS)	0.0018	0.0080	0.012
Non-methane hydrocarbons, VOCs (kg)	0.0017	0.000030	0.000024
Particulate matter, PM_{10} (kg/kg VS)	0.00	0.00	0.00
Particulate matter, $PM_{2.5}$ (kg/kg VS)	0.00	0.00	0.00
Sulphur oxides, SO_x as SO_2 (kg/kg VS)	0.000060	0.000041	0.000033
Hydrogen (kg/ kgVS)	0.00	0.00032	0.00013
Hydrogen sulphide (kg/kg VS)	0.000078	0.000000032	0.00013
Energy output:			
Thermal energy , as heat (MJ/kg VS)	1.00	1.17	0.73
Electrical energy, as electricity (MJ/kg VS)	0.87	1.02	0.64

The following assumptions were made during the inventory datasets development:

- Transport of chemicals from suppliers to the plant site in South Africa is included in the LCA, is done by a medium small truck on a distance of 15 km.
- Data for energy consumption for all processes are included in the LCA evaluation.
- The energy inputs include electricity (South African electricity mix), thermal energy (as heat) and diesel.
- Treatment of wastewater in the municipal treatment works is included in the LCA evaluation.
- Fuel storage is not considered in the LCA.
- The inventory considers the infrastructure for the production and application of the fuel.
- Disposing and transport of end-product is included in the inventory.
- 0.00 stands for no emissions or a real “zero”.

Table 4.8: Life cycle inventory data for the application of biomethane as fuels for compressed biogas vehicles (CBGV)

Inputs	**LCA:Set1: $[X]_k$**	**LCA:Set2: $[X]_k$**	**LCA:Set3: $[X]_k$**
Feedstock:			
Volatile solids (kg/kg VS)	1.00	1.00	1.00
Nutrients:			
$CaCl_2 * 2\ H_2O$, (kg/kg VS)	0.010	0.00	0.00
$CuSO_4$, (kg/kg VS)	0.00025	0.00	0.00
$FeSO_4$, (kg/kg VS)	0.00075	0.0000012	0.00
$MgCl_2$, (kg/kg VS)	0.00075	0.00	0.00
K_2HPO4, (kg/kg VS)	0.033	0.00	0.00
$CoCl_2 \times 6\ H_2O$, (kg/kg VS)	0.0000062	0.00	0.00
Resources:			
Water (kg/kg VS)	0.00	1.79	10.00
Diesel (L/kg VS)	0.0082	0.033	0.011
Hydrochloric acid (kg/kg VS)	0.036	0.00	0.00
Sodium hydroxide (kg/kg VS)	0.036	0.00	0.00
Energy:			
Electrical energy (MJ/kg VS)	0.83	0.95	0.60
Outputs			
Effluents:			
Volatile solids, (kg/kg VS)	0.090	0.30	0.18
Phosphate, (kg/kg VS)	0.000028	0.000023	0.0062
Nitrogen, (kg/kg VS)	0.000040	0.000021	0.037
Ammonia, as NH_3-N, (kg/kg VS)	0.00	0.00	0.0094
Sodium hydroxide, (kg/kg VS)	0.00	0.00	0.00
Gases:			
Carbon dioxide, (kg/kg VS)	1.55	1.99	1.25
Carbon monoxide, (kg/kg VS)	0.00	0.00	0.00
Benzene (kg/kg VS)	0.00	0.00	0.00
Formaldehyde, (kg/kg VS)	0.00	0.00	0.00
Methane, (kg/kg VS)	1.75	2.05	1.29
Nitrogen oxides, NO_X as NO_2, (kg/kg VS)	0.000076	0.057	0.071
Non-methane hydrocarbons, VOCs, (kg/kg VS)	0.00	0.00	0.00
Particulate matter, PM_{10}, (kg/kg VS)	0.00	0.00	0.00
Particulate matter, $PM_{2.5}$, (kg/kg VS)	0.00	0.00	0.00
Sulphur oxides, SO_x as SO_2, (kg/kg VS)	0.00	0.00	0.00
Hydrogen, (kg/kg VS)	0.00	0.00041	0.00013
Hydrogen sulphide, (kg/kg VS)	0.000078	0.000000032	0.0013
Vehicle performance:			
Distance travelled by vehicle (km/kg VS)	2.67	3.13	1.96

The following assumptions were made during the inventory datasets development:

- Transport of chemicals from suppliers to the plant site in South Africa is included in the LCA, is done by a medium small truck on a distance of 15 km.
- Data for energy consumption for all processes are included in the LCA evaluation.
- The energy inputs include electricity (South African electricity mix), thermal energy (as heat) and diesel.
- Treatment of wastewater in the municipal treatment works is included in the LCA evaluation.
- Compression and distribution of the fuel the vehicle tank is considered in the inventory.
- Fuel storage is not considered in the LCA.
- Inventory does not consider the manufacturing and disposing of the vehicles.
- Compressed natural gas vehicles (CNG vehicles) production is excluded
- 0.00 stands for no emissions or a real “zero”.

Table 4.9: Life cycle inventory data for electricity generation from biohydrogen produced from three different organic wastes

Inputs	**LCA:Set1: $[Y]_m$**	**LCA:Set2: $[Y]_m$**	**LCA:Set3: $[Y]_m$**
Feedstock:			
Volatile solids (kg/kg VS)	1.00	1.00	1.00
Nutrients:			
$CaCl_2 * 2 H_2O$, (kg/kg VS)	0.010	0.00	0.00
$CuSO_4$, (kg/kg VS)	0.00025	0.00	0.00
$FeSO_4$, (kg/kg VS)	0.0011	0.0000012	0.00
$MgCl_2$, (kg/kg VS)	0.00075	0.00	0.00
K_2HPO4, (kg/kg VS)	0.033	0.00	0.00
$CoCl_2$ x 6 H_2O, (kg/kg VS)	0.000062	0.00	0.00
Resources:			
Water (kg/kg VS)	0.00	1.79	10.00
Diesel (L/kg VS)	0.00	0.033	0.0068
Hydrochloric acid (kg/kg VS)	0.073	0.00	0.00
Sodium hydroxide (kg/kg VS)	0.073	0.00	0.00
Energy:			
Electrical energy (MJ/kg VS)	0.032	0.20	0.14
Outputs			
Effluent Output:			
Volatile solids (kg/kg VS)	0.0081	0.00089	0.42
VFA, as acetate (kg/kg VS)	0.00	0.000086	0.00
Phosphate (kg/kg VS)	0.000028	0.00	0.0062
Nitrogen (kg/kg VS)	0.000012	0.00	0.037
Ammonia, as NH_3-N (kg/kg VS)	0.00	0.00	0.0094
Sodium hydroxide, (kg/kg VS)	0.020	0.00	0.00
Gases:			
Carbon dioxide (kg/kg VS)	1.87	0.31	6.83
Carbon monoxide (kg/kg VS)	0.00	0.00	0.00
Benzene (kg/kg VS)	0.00	0.00	0.00
Formaldehyde (kg/kg VS)	0.00	0.00	0.00
Methane (kg/kg VS)	0.00	0.00	0.00
Nitrogen oxides, NO_x as NO_2 (kg/kg VS)	0.0053	0.0067	0.00
Non-methane hydrocarbons, VOCs (kg)	0.00	0.00	0.00
Particulate matter, PM_{10} (kg/kg VS)	0.0000049	0.00000061	0.00000019
Particulate matter, $PM_{2.5}$ (kg/kg VS)	0.0000017	0.00000022	0.000000069
Sulphur oxides, SO_x as SO_2 (kg/kg VS)	0.00	0.00	0.00
Hydrogen (kg/ kgVS)	0.0022	0.00028	0.000088
Hydrogen sulphide (kg/kg VS)	0.0053	0.00000052	0.00000017
Energy output:			
Thermal , as heat (MJ/kg VS)	0.24	0.070	0.040
Electrical, as electricity (MJ/kg VS)	1.06	0.31	0.19

The following assumptions were made during the inventory datasets development:

- Transport of chemicals from suppliers to the plant is included in the inventory (done by a medium small truck on a distance of 15 km).
- Data for energy consumption is included in the inventory.
- The energy inputs include electricity (South African electricity mix), thermal energy (as heat) and diesel.
- Treatment of wastewater in the municipal treatment works is included in the inventory.
- Fuel storage is not considered in the LCA.
- The inventory does not consider the decommissioning of the fuel production infrastructure.
- 0.00 stands for no emissions or a real "zero".

Table 4.10: Life cycle inventory data for the application of biohydrogen as fuels for fuel cell vehicles (FC vehicle)

Inputs	**LCA:Set1: $[Y]_k$**	**LCA:Set2:$[Y]_k$**	**LCA:Set3: $[Y]_k$**
Feedstock:			
Volatile solids (kg/kg VS)	1.00	1.00	1.00
Nutrients:			
$CaCl_2$ * 2 H_2O, (kg/kg VS)	0.010	0.00	0.00
$CuSO_4$, (kg/kg VS)	0.033	0.00	0.00
$FeSO_4$, (kg/kg VS)	0.0011	0.0000012	0.00
$MgCl_2$, (kg/kg VS)	0.00075	0.00	0.00
K_2HPO4, (kg/kg VS)	0.033	0.00	0.00
$CoCl_2$ x 6 H_2O, (kg/kg VS)	0.0000062	0.00	0.00
Resources:			
Water (kg/kg VS)	0.000	1.79	10.00
Diesel (L/kg VS)	0.36	0.033	0.0068
Hydrochloric acid (kg/kg VS)	0.073	0.00	0.00
Sodium hydroxide (kg/kg VS)	0.073	0.00	0.00
Energy input:			
Electrical energy (MJ/kg VS)	0.40	0.31	0.21
Output			
Effluents:			
Volatile solids, (kg/kg VS)	0.0081	0.00	0.42
Phosphate, (kg/kg VS)	0.000028	0.00	0.0062
Nitrogen, (kg/kg VS)	0.000012	0.00	0.037
Ammonia, as NH_3-N, (kg/kg VS)	0.000	0.00	0.0094
Sodium hydroxide, (kg/kg VS)	0.020	0.00	0.00
Gases:			
Carbon dioxide, (kg/kg VS)	2.44	0.39	6.86
Carbon monoxide, (kg/kg VS)	0.000	0.00	0.00
Formaldehyde, (kg/kg VS)	0.000	0.00	0.00
Methane, (kg/kg VS)	1.43	0.18	0.057
Nitrogen oxides, NO_X as NO_2, (kg/kg VS)	0.0053	0.0067	0.00
Non-methane hydrocarbons, VOCs, (kg/kg VS)	0.000	0.00	0.00
Particulate matter, PM_{10}, (kg/kg VS)	0.0000048	0.00000061	0.00000019
Particulate matter, $PM_{2.5}$, (kg/kg VS)	0.0000017	0.00000022	0.000000069
Sulphur oxides, SO_x as SO_2, (kg/kg VS)	0.0024	0.00030	0.000095
Hydrogen, (kg/kg VS)	0.0022	0.00028	0.000088
Hydrogen sulphide, (kg/kg VS)	0.000000041	0.00000052	0.00000017
Vehicle performance:			
Distance travelled by vehicle (km/kg VS)	4.35	1.27	0.79

The following assumptions were made during the inventory datasets development:

- Transport of chemicals from suppliers to the plant site in South Africa is included in the LCA, is done by a medium small truck on a distance of 15 km.
- Data for energy consumption for all processes are included in the LCA evaluation.
- The energy inputs include electricity (South African electricity mix), thermal energy (as heat) and diesel.
- Treatment of wastewater in the municipal treatment works is included in the LCA evaluation.
- Compression and distribution of the fuel the vehicle tank is considered in the LCA.
- Fuel storage is not considered in the LCA.
- The inventory does not consider the decommissioning of the fuel production infrastructure.
- Disposing and transport of end-product is included in the inventory.
- Fuel cell (FC) vehicle production is excluded
- 0.00 stands for no emissions or a real "zero".

Table 4.11: Life cycle impact assessment (LCIA) results showing potential impacts for the application of the gaseous biofuels in electricity generation systems and vehicle operation.

Study scenarios	**Climate change Human Health (DALY)**	**Climate change Ecosystems (species.yr)**	**Fossil depletion ($)**	**Freshwater Ecotoxicity (species.yr)**	**Freshwater Eutrophication (species.yr)**	**Human toxicity (DALY)**	**Ionising radiation (DALY)**	**Metal depletion ($)**	**Ozone depletion (DALY)**	**Particulate matter Formation (DALY)**	**Photochemical oxidant formation (DALY)**	**Terrestrial Acidification (species.yr)**	**Terrestrial Ecotoxicity (species.yr)**
LCA:Set1: [X]m	4.90E-07	2.77E-09	1.05E+00	9.31E-13	2.11E-11	1.42E-07	1.50E-09	1.99E-03	2.68E-11	2.13E-07	8.83E-11	1.49E-11	2.93E-12
LCA:Set2: [X]m	7.00E-07	3.96E-09	2.98E+00	6.44E-13	4.44E-12	7.54E-08	3.68E-10	1.87E-03	1.34E-09	8.27E-07	5.47E-10	4.87E-11	3.25E-12
LCA:Set3: [X]m	1.99E-07	1.13E-09	5.04E-01	7.36E-13	2.94E-12	4.82E-08	1.10E-10	1.32E-03	6.47E-11	7.58E-07	4.87E-10	4.41E-11	1.56E-12
LCA:Set1: [Y]m	5.63E-07	3.19E-09	1.57E+00	1.30E-12	9.15E-12	2.07E-07	1.22E-09	7.47E-03	7.52E-11	2.61E-07	6.96E-11	1.22E-11	5.44E-12
LCA:Set2: [Y]m	5.03E-07	2.85E-09	4.15E+00	9.56E-13	2.33E-12	5.04E-08	4.52E-10	1.64E-03	2.12E-09	4.56E-07	3.16E-10	2.61E-11	4.52E-12
LCA:Set3: [Y]m	6.74E-07	3.81E-09	1.97E+00	1.68E-12	8.74E-12	1.63E-07	6.43E-10	6.30E-03	4.16E-10	2.74E-07	7.49E-11	1.73E-11	4.36E-12
LCA:Set1: [X]k	6.47E-07	3.66E-09	1.49E+00	1.15E-12	2.40E-11	1.67E-07	1.52E-09	1.75E-03	9.69E-11	2.35E-07	6.52E-11	1.80E-11	8.20E-12
LCA:Set2: [X]k	8.88E-07	5.02E-09	3.54E+00	9.05E-13	7.56E-12	1.05E-07	3.68E-10	1.68E-03	1.44E-09	8.63E-07	5.24E-10	5.29E-11	9.18E-12
LCA:Set3: [X]k	3.13E-07	1.77E-09	8.31E-01	9.05E-13	1.46E-15	6.68E-08	1.09E-10	1.20E-03	1.17E-10	7.85E-07	4.75E-10	4.70E-11	5.26E-12
LCA:Set1: [Y]k	7.76E-06	4.38E-08	6.03E+00	1.39E-12	9.80E-12	2.26E-07	1.54E-09	7.14E-03	3.15E-09	3.58E-07	2.65E-10	1.90E-11	6.95E-12
LCA:Set2: [Y]k	3.14E-07	1.77E-09	1.25E+00	3.20E-13	2.67E-12	3.71E-08	1.30E-10	5.92E-04	5.10E-10	3.50E-07	1.85E-10	1.87E-11	3.24E-12
LCA:Set3: [Y]k	4.58E-06	2.58E-08	7.30E-01	3.63E-13	2.18E-12	3.66E-08	1.35E-10	9.48E-04	2.66E-10	7.07E-08	8.07E-11	4.69E-12	9.12E-13
Total impacts	1.76E-05	9.95E-08	2.61E+01	1.13E-11	9.49E-11	1.32E-06	8.10E-09	3.39E-02	9.62E-09	5.45E-06	3.18E-09	3.24E-10	5.58E-11

Table 4.12: Environmental impact assessment results for the comparison of the application of gaseous biofuels in electricity generation systems and vehicles operations.

Study scenarios	Climate change Human Health	Climate change Ecosystems	Fossil depletion	Freshwater ecotoxicity	Freshwater eutrophication	Human toxicity	Ionising radiation	Metal depletion	Ozone depletion	Particulate matter formation	Photochemical oxidant formation	Terrestrial acidification	Terrestrial ecotoxicity	Total impacts
LCA:Set1: [X]m	0.028	0.028	0.040	0.083	0.22	0.11	0.19	0.059	0.0028	0.039	0.028	0.046	0.053	0.92
LCA:Set2: [X]m	0.040	0.040	0.11	0.057	0.047	0.057	0.045	0.055	0.14	0.15	0.17	0.15	0.058	1.13
LCA:Set3: [X]m	0.011	0.011	0.019	0.065	0.031	0.036	0.014	0.039	0.0067	0.14	0.15	0.14	0.028	0.69
LCA:Set1: [Y]m	0.032	0.032	0.060	0.12	0.096	0.16	0.15	0.22	0.0078	0.048	0.022	0.038	0.097	1.08
LCA:Set2: [Y]m	0.029	0.029	0.16	0.085	0.025	0.038	0.056	0.048	0.22	0.084	0.099	0.081	0.081	1.03
LCA:Set3: [Y]m	0.038	0.038	0.075	0.15	0.092	0.12	0.079	0.19	0.043	0.050	0.024	0.053	0.078	1.03
LCA:Set1: [X]k	0.037	0.037	0.057	0.10	0.25	0.13	0.19	0.052	0.010	0.043	0.021	0.056	0.15	1.13
LCA:Set2: [X]k	0.050	0.050	0.14	0.080	0.080	0.079	0.045	0.050	0.15	0.158	0.16	0.16	0.16	1.37
LCA:Set3: [X]k	0.018	0.018	0.032	0.080	0.000	0.050	0.013	0.035	0.012	0.144	0.15	0.15	0.094	0.79
LCA:Set1: [Y]k	0.44	0.44	0.23	0.12	0.103	0.17	0.19	0.21	0.33	0.066	0.083	0.059	0.12	2.57
LCA:Set2: [Y]k	0.018	0.018	0.048	0.028	0.028	0.028	0.016	0.017	0.053	0.064	0.058	0.058	0.058	0.49
LCA:Set3: [Y]k	0.26	0.26	0.028	0.032	0.023	0.028	0.017	0.028	0.028	0.013	0.025	0.014	0.016	0.77

4.2. Life cycle costing (LCC) results

The life cycle costing (LCC) was used to determine the financial feasibility of the gaseous biofuel infrastructural development according to the methodological approach discussed in section 3.5. The methodological approach towards the life cycle inventory analysis, evaluating economic impact assessment, and life cycle interpretation phase is discussed in the following sections 3.5.1, 3.5.2, and 3.5.3, respectively. The economic performance considers the following impact indicators, namely: i.e. net present value (NPV), internal rate of return (IRR) and the payback period (PBP). The results for the economic performance of the production and application of gaseous biofuels are presented in Table 4.13 to 4.15.

Table 4.13: Life cycle costing results for the comparison of the study settings for electricity generation systems and vehicles operations.

Study scenarios	NPV (R)	IRR (%)	PBP (year)
LCC:Set1: [X]m	2.91	14.22	5.41
LCC:Set2: [X]m	4.67	17.12	4.14
LCC:Set3: [X]m	1.26	12.59	6.22
LCC:Set1: [Y]m	3.25	14.72	5.24
LCC:Set2: [Y]m	-6.06	-11.69	-28.45
LCC:Set3: [Y]m	-5.15	-21.02	-23.17
LCC:Set1: [X]k	2.74	13.90	5.40
LCC:Set2: [X]k	4.44	16.63	4.13
LCC:Set3: [X]k	1.18	12.36	6.15
LCC:Set1: [Y]k	0.30	10.43	7.00
LCC:Set2: [Y]k	-6.92	-18.25	-19.58
LCC:Set3: [Y]k	-5.69	-21.02	-18.07
Total value	20.74	111.97	43.68
Note: NPV = Net present value; IRR = Internal rate of return; PBP = Payback period; R = Rands; % = percentage.			

Table 4.14: life cycle costing results showing percentage contribution for each economic indicators for all the study scenarios.

Study Scenarios	NPV (%)	IRR (%)	PBP (%)
LCC:Set1: [X]m	14.01	12.70	12.39
LCC:Set2: [X]m	22.50	15.29	9.47
LCC:Set3: [X]m	6.07	11.24	14.23
LCC:Set1: [Y]m	15.67	13.15	11.99
LCC:Set2: [Y]m	-29.22	-10.44	-65.13
LCC:Set3: [Y]m	-24.84	-18.78	-53.04
LCC:Set1: [X]k	13.20	12.41	12.35
LCC:Set2: [X]k	21.43	14.85	9.46
LCC:Set3: [X]k	5.67	11.04	14.07
LCC:Set1: [Y]k	1.46	9.31	16.03
LCC:Set2: [Y]k	-33.37	-16.30	-44.82
LCC:Set3: [Y]k	-27.43	-18.78	-41.36
Note: NPV = Net present value; IRR = Internal rate of return; PBP = Payback period.			

Table 4.15: Economic impact assessment results for the comparison of the application of gaseous biofuels in electricity generation systems and vehicles operations.

Study scenarios	NPV	IRR	PBP	Economic performance
LCC:Set1: [X]m	0.65	0.58	0.53	1.75
LCC:Set2: [X]m	1.00	0.70	0.65	2.35
LCC:Set3: [X]m	0.30	0.53	0.45	1.28
LCC:Set1: [Y]m	0.73	0.60	0.55	1.88
LCC:Set2: [Y]m	0.00	0.00	0.00	0.00
LCC:Set3: [Y]m	0.00	0.00	0.00	0.00
LCC:Set1: [X]k	0.60	0.58	0.53	1.70
LCC:Set2: [X]k	0.95	0.68	0.65	2.28
LCC:Set3: [X]k	0.30	0.53	0.45	1.28
LCC:Set1: [Y]k	0.10	0.45	0.38	0.93
LCC:Set2: [Y]k	0.00	0.00	0.00	0.00
LCC:Set3: [Y]k	0.00	0.00	0.00	0.00

Note: NPV = Net present value; IRR = Internal rate of return; PBP = Payback period; and 0.00 = real "zero" or negative value (A negative NPV and IRR indicates that the project will be making a loss as the project's cost incurred are greater than the projected income. Additionally, a negative PBP is not viable given that it is calculated in years. These negative values are not sustainable and were therefore assigned the value 0.00 on the sustainability weighting system as indicated in the table above.

4.3 Social-life cycle assessment (S-LCA) results

The social performance of the processes was conducted by using the social life cycle assessment (S-LCA) approach presented in section 3.6. The methodological approach towards generation of the inventory data for the social performance was discussed in details in section 3.6.1. The social inventory data is collected through the questionnaire to obtain both quantitative and qualitative data from onsite-specific locations whereby biodigester systems are installed. The social life cycle impact assessment (S-LCIA) is discussed in section 3.6.2 providing the approach towards social indicator selection for different stakeholders considered in this study. The social impact interpretation phase is discussed in section 3.6.3, which provide detailed methodological approach for the social performance results that are listed in Table 4.16 and 4.17.

Table 4.16: Social-life cycle assessment (S-LCA) inventory data for the comparison application of the gaseous biofuels in electricity generation systems and vehicles operations.

Study Scenarios	Availability of resources	Community engagement	Knowledge and skill development	Safe and healthy living conditions	Consumer savings	Responsibility of the technology	Existence of infrastructure for the technology	Health and safety regulations	Energy efficiency of the technology
S-LCA:Set1: [X]m	0.70	0.50	0.50	0.50	0.70	0.50	0.70	0.50	0.70
S-LCA:Set2: [X]m	0.50	0.70	0.70	0.70	0.50	0.70	0.90	0.90	0.70
S-LCA:Set3: [X]m	1.00	0.50	0.90	0.70	0.70	0.90	1.00	0.70	0.90
S-LCA:Set1: [Y]m	0.50	0.50	0.70	0.70	0.50	0.70	0.90	0.70	0.50
S-LCA:Set2: [Y]m	0.70	0.70	0.90	0.70	0.90	0.90	0.70	0.50	0.90
S-LCA:Set3: [Y]m	0.70	0.50	0.50	0.40	0.40	0.50	0.40	0.50	0.50
S-LCA:Set1: [X]k	0.70	0.70	0.70	0.90	0.90	0.50	0.70	0.70	0.70
S-LCA:Set2: [X]k	0.70	0.70	0.70	0.70	0.70	0.70	0.90	0.70	0.70
S-LCA:Set3: [X]k	0.90	0.50	0.70	0.50	0.50	0.90	1.00	0.50	0.50
S-LCA:Set1: [Y]k	0.50	0.70	0.70	0.70	0.40	0.10	0.70	0.70	0.50
S-LCA:Set2: [Y]k	0.70	0.70	0.70	0.50	0.90	0.90	0.50	0.70	0.90
S-LCA:Set3: [Y]k	0.70	0.50	0.50	0.40	0.40	0.50	0.40	0.50	0.50
Total impact	8.30	7.20	8.20	7.40	7.50	7.80	8.80	7.60	8.00

Table 4.17: Social impact assessment results for the comparison of the application of gaseous biofuels in electricity generation systems and vehicles operations.

Study Scenarios	Availability of resources	Community engagement	Knowledge and skill development	Safe and healthy living conditions	Consumer savings	Responsibility of the technology	Existence of infrastructure for the	Health and safety regulations	Energy efficiency of the technology	Social performance
S-LCA:Set1: [X]m	0.084	0.069	0.061	0.068	0.093	0.064	0.080	0.066	0.088	0.67
S-LCA:Set2: [X]m	0.060	0.097	0.085	0.095	0.067	0.090	0.10	0.12	0.088	0.80
S-LCA:Set3: [X]m	0.12	0.069	0.11	0.095	0.093	0.12	0.11	0.092	0.11	0.92
S-LCA:Set1: [Y]m	0.060	0.069	0.085	0.095	0.067	0.090	0.10	0.092	0.063	0.72
S-LCA:Set2: [Y]m	0.084	0.097	0.110	0.095	0.12	0.115	0.080	0.066	0.113	0.88
S-LCA:Set3: [Y]m	0.084	0.069	0.061	0.054	0.053	0.064	0.045	0.066	0.063	0.56
S-LCA:Set1: [X]k	0.084	0.097	0.085	0.12	0.12	0.064	0.080	0.092	0.088	0.83
S-LCA:Set2: [X]k	0.084	0.097	0.085	0.095	0.093	0.090	0.102	0.092	0.088	0.83
S-LCA:Set3: [X]k	0.11	0.069	0.085	0.068	0.067	0.12	0.11	0.066	0.063	0.75
S-LCA:Set1: [Y]k	0.060	0.097	0.085	0.095	0.053	0.013	0.080	0.092	0.063	0.64
S-LCA:Set2: [Y]k	0.084	0.097	0.085	0.068	0.12	0.12	0.057	0.092	0.11	0.83
S-LCA:Set3: [Y]k	0.084	0.069	0.061	0.054	0.053	0.064	0.045	0.066	0.063	0.56

4.4 Life cycle sustainability assessment (LCSA) results

The life cycle sustainability assessment (LCSA) was conducted following the methodological approach discussed in section 3.3. Each dimension of sustainability for example environment, economic and social aspects was modelled using the following life cycle tools: LCA evaluates the environmental aspect (section 3.4), and LCC examines the economic point of view (section 3.5), and S-LCA focuses on the social performance (section 3.6). Then, these three life cycle tools (i.e. LCA, LCC and S-LCA) are then used as the sub-methodologies to represent the integrated life cycle sustainability assessment (LCSA) framework according to the methodological approach which is describe in details in section 3.3.

The results for the sustainability performance index (SPI) values for all the study scenarios generated in this study are shown in Table 4.18, 4.19 and 4.20. The results presents the sustainability performance for the comparison of the application of biomethane vs. biohydrogen produced in different settings, namely: agro-industrial, urban and rural settings. The gaseous biofuels, i.e. biomethane vs. biohydrogen were used as fuels for application in electricity generation systems (i.e. combined heat and power (CHP) systems or fuel cell (FC) systems) and also in vehicles (i.e. compressed natural gas (CNGV) or fuel cell vehicle (FCV)).

Table 4.18: Holistic integration of the three dimension of sustainability for all the study scenarios generated in this study.

Study Scenarios	LCA	LCC	S-LCA
LCSA:Set1: [X]m	0.92	1.75	0.67
LCSA:Set2: [X]m	1.13	2.35	0.80
LCSA:Set3: [X]m	0.69	1.28	0.92
LSCA:Set1: [Y]m	1.08	1.88	0.72
LCSA:Set2: [Y]m	1.03	0.00	0.88
LCSA:Set3: [Y]m	1.03	0.00	0.56
LCSA:Set1: [X]k	1.13	1.70	0.83
LCSA:Set2: [X]k	1.37	2.28	0.83
LCSA:Set3: [X]k	0.79	1.28	0.75
LCSA:Set1: [Y]k	2.57	0.93	0.64
LCSA:Set2: [Y]k	0.49	0.00	0.83
LCSA:Set3: [Y]k	0.77	0.00	0.56
Total value	13.00	13.43	9.00

Table 4.19: Normalized percentage values for the three dimension of sustainability in the selected study settings

Study Scenarios	LCA (%)	LCC (%)	S-LCA (%)
LCSA:Set1: [X]m	7.08	13.04	7.47
LCSA:Set2: [X]m	8.67	17.50	8.91
LCSA:Set3: [X]m	5.31	9.50	10.24
LSCA:Set1: [Y]m	8.28	13.97	8.03
LCSA:Set2: [Y]m	7.94	0.00	9.77
LCSA:Set3: [Y]m	7.92	0.00	6.22
LCSA:Set1: [X]k	8.67	12.66	9.24
LCSA:Set2: [X]k	10.55	16.95	9.18
LCSA:Set3: [X]k	6.09	9.50	8.39
LCSA:Set1: [Y]k	19.76	6.89	7.09
LCSA:Set2: [Y]k	3.79	0.00	9.24
LCSA:Set3: [Y]k	5.93	0.00	6.22

The normalised percentage values in table 4.19 above of each sustainability measure are used to obtain the sustainability performance index based on the weight they carry. The weighting system developed and presented in Appendix 11 provides a scaling system that matches a percentage intervals to a single weight ranging from 0-1. Different weights are then assigned to the respective normalised percentages in order to explain their level of sustainability. In this study, it was specified that the three dimension of sustainability (i.e. environment, economic and social) have the same weight, but the indicators chosen have different percentages of contribution towards the overall sustainability performance. In order to relate them to a manageable and comparable number, the choice of indictors were classified as positive indicators and negative indicators. Negative indicators are those that high values have a negative contribution to sustainability (i.e. environmental indicators) and positive indicators are those that have a positive contribution to sustainability (i.e. economic and social indicators). Therefore, the weighting system was developed to transform the percentage values into score impact factors to present the overall sustainability performance index (SPI) value as presented in Table 4.20.

Table 4.20: Life cycle sustainability assessment results are presented as the sustainability performance index (SPI) for each scenarios developed in this study.

Agro-Industrial: Brewery Wastewater				
Study Scenarios	**LCA**	**LCC**	**S-LCA**	**LCSA**
LCSA:Set1: [X]m	0.75	0.60	0.38	1.73
LCSA:Set1: [X]k	0.68	0.60	0.45	1.73
LCSA:Set1: [Y]m	0.70	0.65	0.40	1.75
LCSA:Set1: [Y]k	0.20	0.35	0.35	0.90
Urban: Organic Fraction of Municipal Solid Waste (OFMSW)				
Study Scenarios	**LCA**	**LCC**	**S-LCA**	**LCSA**
LCSA:Set2: [X]m	0.68	0.80	0.43	1.90
LCSA:Set2: [X]k	0.60	0.78	0.45	1.83
LCSA:Set2: [Y]m	0.73	0.00	0.48	1.20
LCSA:Set2: [Y]k	0.90	0.00	0.45	1.35
Rural: Cattle Manure				
Study Scenarios	**LCA**	**LCC**	**S-LCA**	**LCSA**
LCSA:Set3: [X]m	0.83	0.45	0.48	1.75
LCSA:Set3: [X]k	0.83	0.45	0.40	1.68
LCSA:Set3: [Y]m	0.73	0.00	0.30	1.03
LCSA:Set3: [Y]k	0.80	0.00	0.30	1.10

5. CHAPTER 5: DISCUSSION OF THE LIFE CYCLE SUSTAINABILITY ASSESSMENT IN THE AGRO-INDUSTRIAL SETTING

5.1. Biomethane versus biohydrogen comparison in electricity generation

The agro-industrial setting is described as one of the commercial sectors with a growing demand for electricity to power various kinds of industrial operations. Nowadays, there is increase in the number of anaerobic digestions treatment plants installations in industrial operations. It is believed that the currently existing biomethane infrastructural development will serve as a precursor for the infrastructural development for the hydrogen economy in South Africa. The agro-industrial setting has potential to generate various types of organic waste-based residues (such as brewery wastewater, food waste, etc.) that can be used to recovery energy in the form of methane-containing biogas. For example, the brewery wastewater can easily be channelled into the anaerobic digestion systems to generate biomethane gas. It is very important to consider the type of feedstock selected for the energy generation. The use of the brewery wastewater is advantageous because it is largely available on site and is believed to reduce the costs associated with the collection and transportation of the feedstocks. Again, feedstocks have different characteristics and depending on the choice of the technology, the production yields differs during energy generation process.

This section discusses the results for the comparison of the sustainability performance of the application of biomethane versus biohydrogen in the electricity generation systems. Figure 17.5 shows that the biohydrogen technology records slightly higher sustainability performance index (SPI) value of 1.75, when compared to the biomethane technology which records the SPI value of 1.73. The results indicate that the use of biohydrogen in the fuel cell (FC) systems has the most sustainability performance outcome when compared to the biomethane use in combined heat and power (CHP) systems. The biohydrogen technology offers promising prospects for the installation in the agro-industrial settings for the generation of electricity. Therefore, the existing biomethane infrastructural development in the agro-industrial settings can be used for the introduction of the biohydrogen technology for electricity generation.

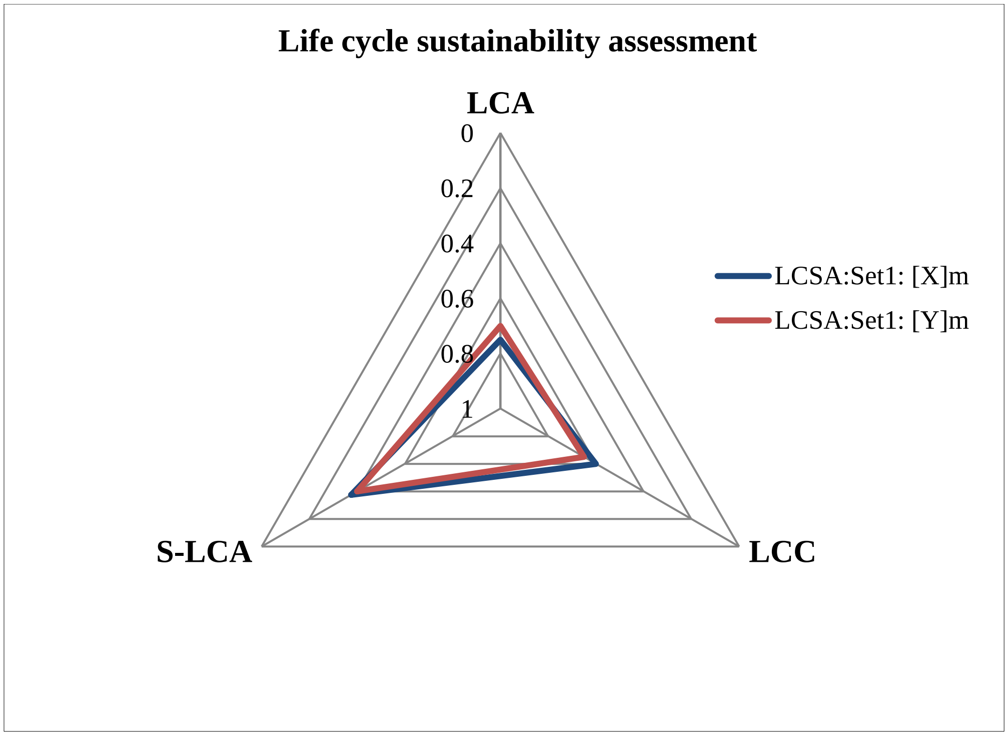

Figure 17.5 Comparison of sustainability performance of biomethane and biohydrogen produced from brewery wastewater for application in electricity generation processes.

Considering the environmental performance, the biomethane technology has environmental performance value of 0.75, when compared to the biohydrogen technology, which records the value of 0.70. The biomethane technology improves the environmental performance when compared to the biohydrogen technology for the comparison of the energy fuels in the electricity generation systems. The biomethane technology offers the reduction of environmental burdens for the entire cradle-to-grave assessment of the technology. This suggests that all the stages of the biomethane technology are sustainable from the collection and pretreatment of brewery wastewater, bioconversion process, and the application of the biohydrogen in electricity generation systems. The biohydrogen technology has the highest electricity generation value of 1.06 MJ/kg VS of the utilization of brewery wastewater. For the case of the biomethane technology, the electricity generation is lower when compared to the biohydrogen technology with the value of 0.87 MJ/kg VS. The electricity generation from biohydrogen generated from brewery wastewater is promising for implementation in the agro-industrial settings. The selection of the feedstock for energy generation and the choice of technology to be implemented are very important to consider in order to achieve the sustainability development. For this case, the brewery wastewater has proved to be suitable feedstock for the electricity generation in the agro-industrial settings. The brewery wastewater does reduce significantly the environmental burdens that are associated with the collection and the pretreatment stages of the brewery wastewater and thus improving the environmental performance of the biohydrogen technology.

In the case of the bioconversion process, the biohydrogen technology requires high energy demand and chemical inputs for the thermophilic dark fermentation process. It is very important to ensure that the production yields of the thermophilic dark fermentation process are competitive in order to improve the economic performance of the biohydrogen technology. The results of this study demonstrate that the application of gaseous biofuels application (biomethane vs. biohydrogen) in the electricity generation systems offers sustainable outcome in the agro-industrial settings. Therefore, the implementation of the biohydrogen technology is expected to address some of the challenges we are currently facing in industrial and commercial sector. The biohydrogen technology implementation in the agro-industrial settings promises to offer reduction in the environmental emissions in order to achieve sustainable production and consumption of energy resources. The agro-industrial setting has a responsibility to advance and promote the installation of the sustainable fuels for industrial operations. The government of South Africa has pledge at international level its commitment to reduce its greenhouse emissions into the environment. The implementation of the alternative energy generation technologies will address some of the energy challenges being faced in the country. The biohydrogen technology is still immature when compared to the biomethane technology but the technology is showing excellent competitiveness for application in the agro-industrial settings. Finally, it makes a business sense to start investing in biohydrogen technology for electricity generation in the agro-industrial settings.

The economic dimension plays a crucial role to influence the sustainability performance of the electricity generation from brewery wastewater. The application of biohydrogen technology in the electricity generation systems records higher economic performance value of 0.65, when compared to the biomethane technology which records 0.60. Definitely, the biohydrogen technology offers potential for sustainable economic performance for electricity generation in the agro-industrial setting. This is due to the fact that both the net present value (NPV) and internal rate of return

(IRR) of the biohydrogen application in electricity generation is higher than the biomethane technology, and this is a good indication of the sustainable economic performance of the technology. The biohydrogen technology in the agro-industrial settings has a better opportunity to attract investors and make profit during the operation lifetime of the technology. The agro-industrial setting has access to capital investment, making it easier to invest in the sophisticated energy generating technologies, such as the infrastructural development of the biohydrogen production and application. It is very important to point out that the agro-industrial setting not only has access to capital investment, but also consists of skilled human capacity. The implementation of the biohydrogen technology offers new opportunities for economic opportunities to advance alternative energy options in the agro-industrial settings.

In terms of the social performance, the biohydrogen technology records high social performance value of 0.40, while the biomethane technology records a slightly lower social performance value of 0.38. The successful implementation of technology in the particular geographical location is influence by a wide range of social indicators. The implementation of the biohydrogen technology in the agro-industrial settings requires highly technical skilled technicians for both installation and the implementation of the technology. The agro-industrial setting has access to both skilled human capacity and economic power that can advance the research and development for the biohydrogen technology. The skilled technicians have excellent educational background to support the ground-breaking research development. The biohydrogen faces several challenges that are related to the low production efficiencies of the thermophilic dark fermentation process. Definitely, the agro-industrial sector has the greater opportunity to advance and add value to the implementation of the biohydrogen technology.

5.2. Biomethane versus biohydrogen comparison in vehicle operation

The transportation sector in South Africa consumes a significant amount of energy that is mostly generated from fossil fuel resources (i.e. petroleum and diesel, natural gas, etc.). Unfortunately, the continued utilization of fossil fuels has been reported as a major contributor to greenhouse gas (GHG) emissions. Over the years, alternative transportation fuels such as gaseous biofuels have been promoted as potential energy carriers to address some of the energy challenges in the transportation sector. Figure 18.5 presents the results of the comparison of the application of biomethane versus biohydrogen as transportation fuels. The results show that the use of biomethane as a transportation fuel in CNG vehicles records the sustainability performance index value of 1.73, while the biohydrogen records the worst sustainability performance index value of 0.90. These outcomes suggest that the application of biomethane in CNG vehicles operation offers the most sustainable performance when compared to application of biohydrogen in the FC vehicles. The application of biomethane in the CNG vehicles results to the economic performance value of 0.60, when compared to the application of biohydrogen in FC vehicles which records the value of 0.35. The application of the biohydrogen as a fuel for vehicles in agro-industrial settings offers exciting opportunities for application of biohydrogen technology. This is due to the fact that the application of biohydrogen technology is economically sustainable in the vehicles operations and needs improvements for both the environmental and social dimension in order to achieve high sustainability performance outcomes for application in the agro-industrial settings.

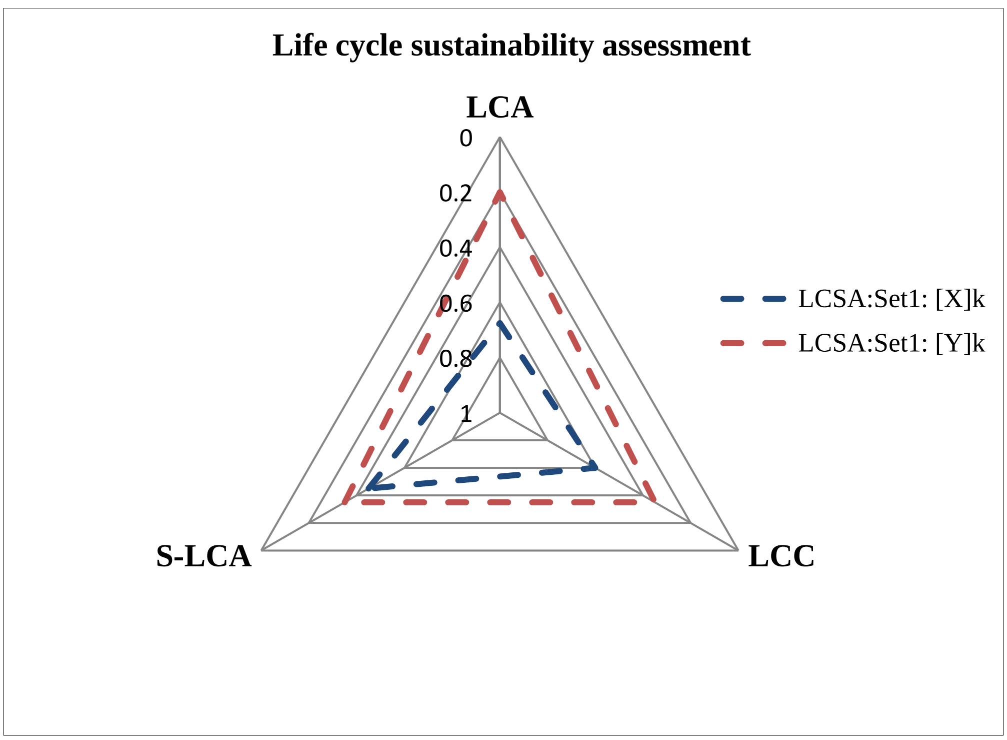

Figure 18.5: Comparison of sustainability performance of biomethane and biohydrogen produced from brewery wastewaters for application in vehicle operations.

The application of biohydrogen in fuel cell vehicles is showing poor performance when it comes to environmental performance. It is showing 3 times worse environmental performance when compared to biomethane application in compressed natural gas (CNG) vehicles. In case of distance travelled by the vehicles, the fuel cell (FC) vehicles travel longer distances with a recorded value of 4.34 km/kg VS, when compared with the compressed natural gas (CNG) vehicles which record 2.67 km/kg VS. The outcome results show the potential of the FC vehicles fuelled with biohydrogen when compared with the CNG vehicles in the agro-industrial settings. Actually, the performance of the FC vehicles is twice as much when compared to the biomethane-fuelled vehicles, which indicates the opportunities that can be achieved through the implementation of the biohydrogen technology. These findings clearly indicate that the biohydrogen technology still requires improvement in order to achieve high sustainability performance in the agro-industrial settings. The energetic value of the gaseous biofuels is dependent on the productivities of the bioconversion process (i.e. anaerobic digestion and thermophilic fermentation process). Again, the energetic value of the fuel also plays a crucial role on the overall sustainability performance by either improving or worsening the economic performance of the technology. It is important to realise that the energy value can be derived from waste-based sources such as brewery wastewater that could have easily been disposed into the municipal wastewater treatment words systems. This provides significant environmental and energy solutions whereby waste-resources are utilized for energy generation and application.

The application of the biomethane in vehicle operation records the highest economic performance value of 0.60. The results clearly indicate that the application of biomethane in compressed natural gas (CNG) vehicles offers a sustainable economic performance, when compared to the biohydrogen application in the fuel cell (FC) vehicles. Among the three dimensions of sustainability the biohydrogen technology is showing promising economic performance for the implementation of the biohydrogen technology in the agro-industrial settings for vehicles operations. It is observed that the economic performance of the biohydrogen technology differs on the results of the application of the fuel (i.e. either in electricity generation, or as fuel for vehicles). Generally, the thermophilic fermentation has low productivities when compared to those of the biomethane technology. It is observed that the application of the energy fuel can further improve or worsen the overall sustainability performance of the technology. In this study, the application of the biohydrogen technology seems sustainable for the application in electricity generation rather than vehicle operation. The application of the biohydrogen technology in vehicle operations has an improved outcome and could be easily inserted for both research development and commercial purposes in the agro-industrial settings.

The sustainability of the energy-generating technologies is very important because the entire cradle-to-grave analysis is conducted. This helps to reveal the stages along the production and application of the energy fuel that needs to be improved. The end-use of the energy carrier plays a crucial role to determine the overall sustainability performance of the technology. The biohydrogen offers great opportunities in the application for the electricity generation when compared to the vehicles operations. Clearly, but for the case of the biomethane technology, the end-application of the technology is quite stable and this reflects the importance of sustainability performance for the technologies. The results clearly show that the sustainability performance of the energy infrastructural development does not only depend on the energy technology that is implemented, but also depends on the end-fuel use for application either in electricity generation systems or as fuel for vehicles. Furthermore, it is important to realize that the energy value of the fuel (biomethane and biohydrogen) is very important to determine the economic performance of the technology.

In terms of the social performance, the biomethane technology commands the highest social sustainability performance value of 0.45, when compared to the biohydrogen technology, which records the value of 0.38 for the application of fuels in the vehicles operations In terms of the application of the energetic fuels such as gaseous biofuels this plays a crucial role for the in determining the social performance of the technologies. The social performance of the technology might consider both social and technological impacts indicators of the technology. It is important to realize that the social performance of the implementation of the particular technology is dependent on the geographical location where the technology is inserted. In this case, both the biomethane and biohydrogen technologies are inserted in the agro-industrial settings requiring a highly skilled technician for the operation of the technologies.

At current conditions, the agro-industrial produces the gaseous biofuels from the brewery wastewater which is easily available in large volumes throughout the season on the industrial plant. There is no requirement for collection and transportation of the brewery wastewater before being pre-treated for the digestion process. It must be noted that pretreatment costs of feedstock are significant and can render the technology uneconomical if not carefully considered. It is important to consider the amount of the availability of the feedstock and the economic potential for the production of the energy carriers from utilizing the brewery wastewater. The utilization of the brewery wastewater for waste-to-energy generation systems is highly mechanized in the agro-industrial setting. Often, industrial operations that are highly mechanized result in job cuts, especially of the low skilled jobs and thus create job opportunities for the high skilled technicians. The installation of the biohydrogen technology can also provide an opportunity for the technology learning, especially for the introduction the infrastructural development for the transportation fuels. During technology learning the agro-industrial setting can effectively provide the inventory data generation. The industrial sector often keeps the inventory data confidential because of competition with other companies. However, this study promotes the need for collaboration between the agro-industrial setting and university research groups to advance the biogas sector in South Africa. The collaboration will provide the opportunities for the inventory data generation and also to identify new stakeholders groups. Furthermore, new market opportunities for application of gaseous biofuels can be developed in the agro-industrial setting.

5.3. Biomethane comparison in electricity generation versus vehicles operation

The agro-industrial sector can play a crucial role in the industrial development of the biogas infrastructural development in South Africa. Biogas is a renewable fuel that can be used for electrical power, heating/cooling, and as a transport fuel. There is a growing number of industrial anaerobic digester systems that are installed for various reasons in the agro-industrial settings. In this case, the agro-industrial setting utilizes the brewery wastewater for the generation of the gaseous biofuels (i.e. biomethane and biohydrogen) for application in the electricity generation and also as fuels for the vehicles. The use of brewer wastewater diverts the disposal of brewery wastewater into municipal treatment works systems, and is used in the energy generation systems. The use of the brewery wastewater results in the reducing economic costs charged for treating the wastewater by municipal wastewater treatment works. Instead, the brewery wastewater is now used for the generation of useful energy carriers for the application in the electricity generation systems or as transportation fuels. The chosen feedstock, brewery wastewater, is always available in large volume throughout the season.

This section discusses the comparison of the application of biomethane in electricity generation systems versus vehicle operation in compressed natural gas vehicles. Figure 19.5 indicates that the application of biomethane in both the CHP systems and CNG vehicles has the same sustainable performance index value estimated at 1.73. Clearly, the use of biomethane for both purposes of electricity generation and as transport fuel delivers a sustainable performance outcome for both cases. The use of the biomethane in the combined heat and power system records the electrical energy output of 0.87 MJ/kg VS. For the case of the application of the biomethane in vehicle operation, the distance travelled by the vehicles is 2.67 km/kg VS. It is important to realize that the agro-industrial sector has the demand for both electricity generation and the transportation fuels. At the current state, the application of the biomethane in the electricity generation and vehicles operations is equally sustainable competitive. The choice of the biomethane application will depend on various factors that need to be considered, but mostly it will consider the economic opportunities that can be obtained from the installation of the biomethane technology.

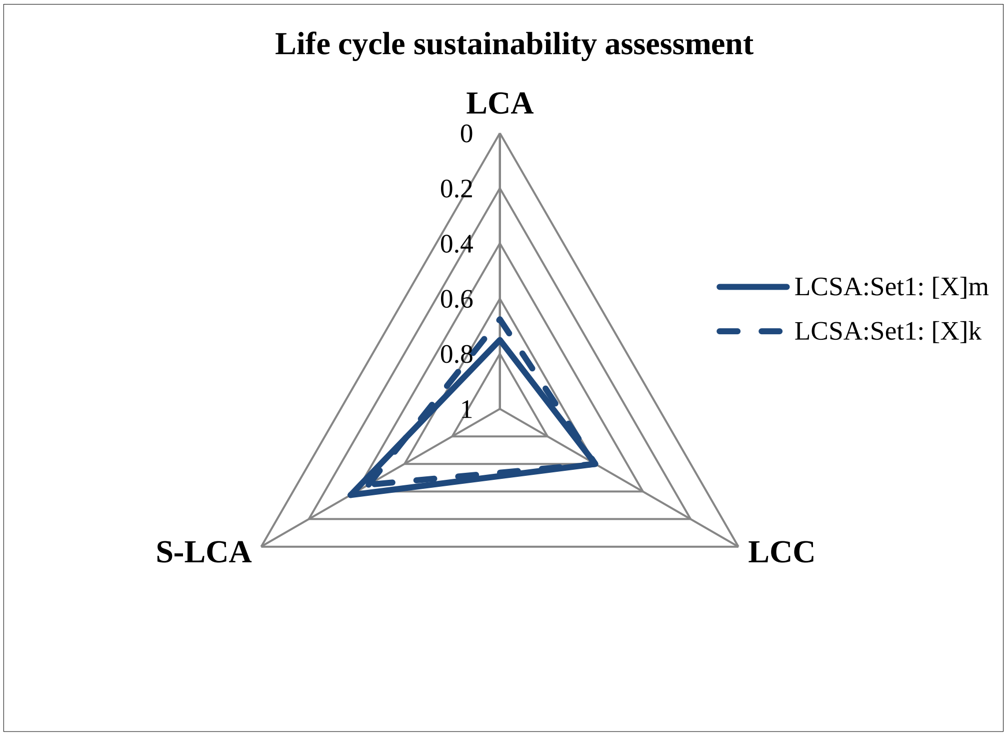

Figure 19.5: Comparison of biomethane produced from brewery wastewater for both applications in the electricity generation processes and also in vehicle operation.

The results of this study suggests that the end-fuel use, especially biomethane, will be determined by the type energy demand (i.e. electricity or transportation fuel) and not by the type of the energy generation technology in the agro-industrial setting. In agro-industrial settings there is equal demand for energy fuels for both application in electricity generation systems and also as fuel for vehicles. In certain areas, a particular energy generation technology cannot be implemented due to the geographical location where the energy technology is implemented. In the agro-industrial setting the biomethane application is both sustainable for the scenarios of electricity generation and also as fuel for vehicles. Therefore, the demand for the fuel end-use will be the deciding factor in the agro-industrial settings. This setting has fuel demand for both application in electricity generation and also vehicles fuels.

The fuel end-use of the biomethane for application in both the electricity generation systems and as transportation is both economically sustainable. The economic performance is almost similar with competitive net present value (NPV), internal rate of return (IRR) and payback period (PBP). This opens up the opportunity for the purchase of the vehicle fuels with biomethane, and this create the opportunity for the infrastructural development in the agro-industrial settings. The compressed natural gas (CNG) vehicles must be less costly when compared to the internal combustion engines (ICE) vehicles using gasoline as fuels in order to advance their demand in the market. The introduction of innovation vehicles is expected to increase in the coming years, and there is a need for the infrastructural development for the vehicles, and the agro-industrial setting provides an opportunity for the technology learning for the introduction of the compressed natural gas (CNG) vehicles in the market.

From the policy point of view, the agro-industrial sector provides real-scale industrial operation systems which are important to drive the policy development for the green energy investments in South Africa. The agro-industrial setting is in a better position to lead the innovation and implementation of the sustainable technologies. For example, the government needs to support the biogas market by providing incentives for operations that generate electricity and also transportation fuels. In this case the incentives might open a market opportunity for the use of the particular fuels, for example many industrial operations will decide on economic opportunities about the implementation of the particular technology. At the moment, many industrial operations are not motivated because there is a lack of clear policy and incentives to support some of the innovative technologies to drive sustainable economy. The agro-industrial setting has an increasing number of anaerobic digestion plants across the country. The most important development is the fact that the biomethane technology has matured, especially for the electricity generation in the combined and heat power systems. There is an opportunity to develop the infrastructural investment for the transportation fuels. The insertion of biomethane as transportation fuel can be achieved through growing the market by establishing excellent incentives and policy frameworks that enable the technology developers to advance they installations.

The infrastructural development requires a platform to develop and identify various stakeholders that promote the advancement of the biogas technology (i.e. investors, entrepreneurs, authorities and law enforcement agencies). The agro-industrial sector can play a leading role to drive towards public awareness campaigns about renewable bioenergy, especially the technology for the gaseous biofuels generation. The agro-industrial setting has attractive economical potential to promote social corporate whereby local communities can benefits through various programmes. This can be done by promoting both the financial support and skill transfer to the local communities through the implementation of the digester systems. This will assist communities to promote the skills transfer through various programmes for the local communities.

5.4. Biohydrogen comparison in electricity generation and vehicle operation

Hydrogen is believed to be the energy carrier of the future. Figure 20.5 presents the results for the comparison of the biohydrogen application in electricity generation systems versus biohydrogen application in vehicles operations. The biohydrogen technology for the use of biohydrogen in fuel cell (FC) systems records the highest sustainability performance index value of 1.75, when compared to the application of the biohydrogen as a transportation fuel in the fuel cell (FC) vehicles. The application of biohydrogen in FC vehicles records the sustainability performance index value of 0.90. Therefore, this presents an opportunity for biohydrogen application for electricity generation in the agro-industrial settings. At the moment, the energetic efficiencies in fuel cells for electrical energy generation have reached the efficiency of approximately 80%. This outcome is great for the research and development in order to promote the implementation of the biohydrogen infrastructural development in the agro-industrial settings. Therefore, the agro-industrial setting might provide the platform for the up-scaling and industrialization of the hydrogen economy, especially for the electricity generation in fuel cell systems.

At cost level, the application of biohydrogen in the electricity generation systems is economically sustainable, recording the value of 0.65, when compared to the biohydrogen use in the vehicles operations. For the case of the application of the energy carrier, the application of the biohydrogen in the biohydrogen in vehicles results in poor economic performance when compared to the application of biohydrogen in electricity generation systems. The economic performance for the application of biohydrogen in FC vehicles records the value of 0.35. The biohydrogen technology is still immature technology which faces several challenges, especially both in the production and application phase. The production of the biohydrogen in thermophilic dark fermentation processes is associated with low biohydrogen production efficiencies. It must be emphasized that both the production and application of the energy carriers play a crucial role to determine the economic performance of the technology.

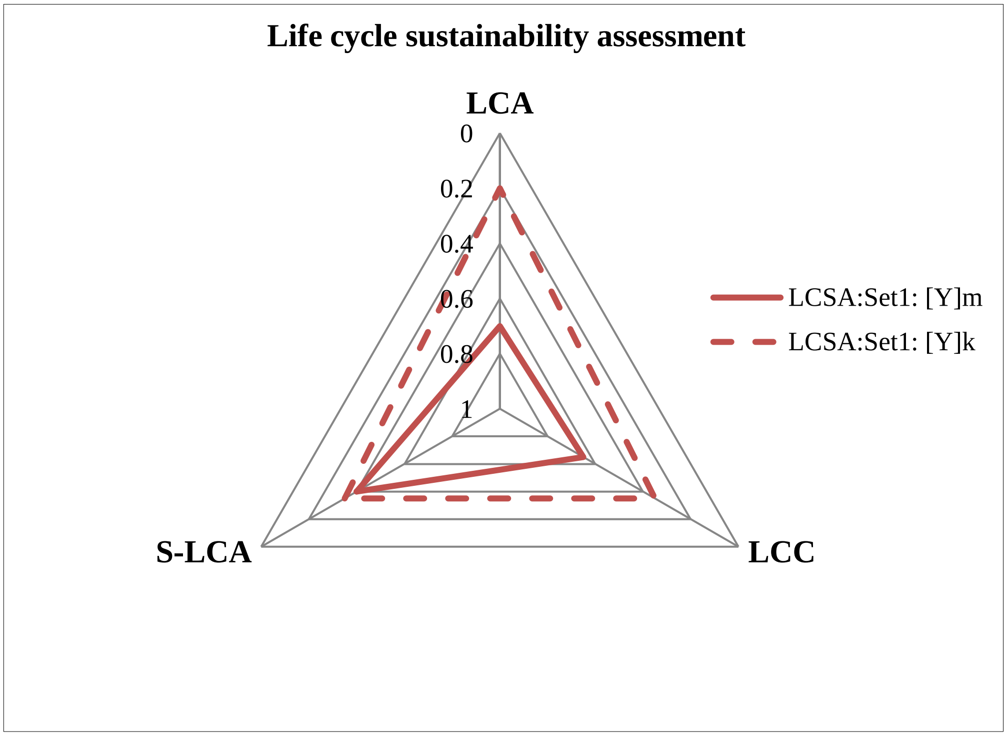

Figure 20.5: Comparison of biohydrogen produced from brewery wastewater for application in the electricity generation and also for vehicle operation.

The economic performance of the application of the biohydrogen in the electricity generation has higher net present value (NPV), internal rate of return (IRR) and payback period (PBP) which is recorded as 3.25, 14.72% and 5.24, respectively. In the case of the biohydrogen application in the vehicles operations the economic performance is lower in terms of NPV, IRR and PBP recording 0.30, 10.43% and 7.00, respectively. The economic performance of the gaseous biofuels is strongly influenced in the entire production and application of the technology. It was observed that the lower biohydrogen production efficiencies in the thermophilic fermentation do affect the economic performance of the biohydrogen technology. Again, the choice of the fuel end-use either in the application for electricity generation or as fuel for transportation vehicles does play a role to influence the sustainability performance of the technology. The biohydrogen technology is rapidly evolving it is expected that the production efficiencies will be improve over time in the future. The agro-industrial setting is the geographical location that is economically attractive and can support the implementation of the innovative technology such as biohydrogen technology. It is important to consider the implementation of technologies that bring about a product with economically sensible practice

Sustainability considers the holistic assessment of three pillars of sustainability, namely: environment, economic and the social dimension, respectively. The sustainability assessment is very important and describes the interconnections and burdens shift among the three dimension of sustainability. The application of biohydrogen in electricity generation show better environmental performance when compared to both the economic and social performance. While, application of biohydrogen in the vehicles operations results to better economic performance when compared to both the social and environmental performances. The introduction of the biohydrogen technology in the agro-industrial setting is expected to bring reduction in the environmental burdens for fuel end-uses in both the electricity and as transportation of the fuels. There is a great potential for the implementation of the biohydrogen technology in the agro-industrial settings, especially the technology for the electricity generation. The agro-industrial setting has both access to economic investments and human skill capacity to operate the biohydrogen production facility. This will definitely drive forward the commercial installation and efficiently operation of the infrastructural development for the biohydrogen technology.

6. CHAPTER 6: DISCUSSION OF THE RESULTS FOR LIFE CYCLE SUSTAINABILITY ASSESSMENT OF THE URBAN SETTING

6.1. Biomethane versus biohydrogen in electricity generation

Generally, the gaseous biofuels (i.e. biomethane and biohydrogen) in urban settings can be produced from inexpensive organic wastes such as organic fraction municipal solid wastes (OFMSW). The OFMSW can be harness from the point of collection and transported to the centralized or decentralized sites with the installed anaerobic digestion treatment plant biogas production. The stages of the collection and transportation of the OFMSW do influence the sustainability outcome of the technology. There is a need to maintain a high quality feedstock for the application in the energy generation systems. It is expected that in the future there will be an increase in the number of installed biogas digester systems in urban areas for the recovery of energy fuels. This section presents the comparison results for the sustainability performance of the comparison of biomethane vs. biohydrogen technologies. Figure 21.6 shows the results that electricity generation using biomethane from organic fraction of municipal solid wastes (OFMSW) offers for an improved sustainability performance index value, which stands at 1.90. For the case of the biohydrogen application in the electricity generation systems, the sustainability performance index value stands at 1.20. The results clearly indicate that the biomethane technology for the electricity generation offers the most sustainable performance outcome when compared with the biohydrogen technology for the electricity generations.

The results clearly show the application of biohydrogen in electricity generation is unsustainable and should be rejected for the implementation at the moment. This is despite the fact that biohydrogen offers interesting desirable properties such as high energy value per unit weight (120 MJ/kg), higher energy yield (approximately 80% of hydrogen is transformed into electricity in fuel cell systems), in combustion process releases with only water as end product. Therefore, hurdles blocking the development of commercial viable biohydrogen generation need to be resolved in order to generate biohydrogen in the sustainable manner. The poor sustainability performance of biohydrogen when compared to biomethane application can be attributed to various factors such as lower conversion efficiencies, higher energy inputs and higher chemical inputs that are required for the dark fermentation process. For example, the anaerobic digestion process for biomethane production operates at lower temperatures between 30-35 °C, whereas thermophilic anaerobic process for biohydrogen generation operates and elevated temperatures between 35-75 °C. This clearly proves that biohydrogen generation will consume more heat due to the higher temperatures required for its production during conversion processes. The key point of criticism is that there is a direct correlation between high energy inputs and negative environmental performance, and high costs of inputs to the process. Therefore, the selection and implementation of the particular energy technology should take into account its sustainability performance, and the sustainability results should be used in decision a making process about the choice of the energy technology to be implemented in the particular geographical location.

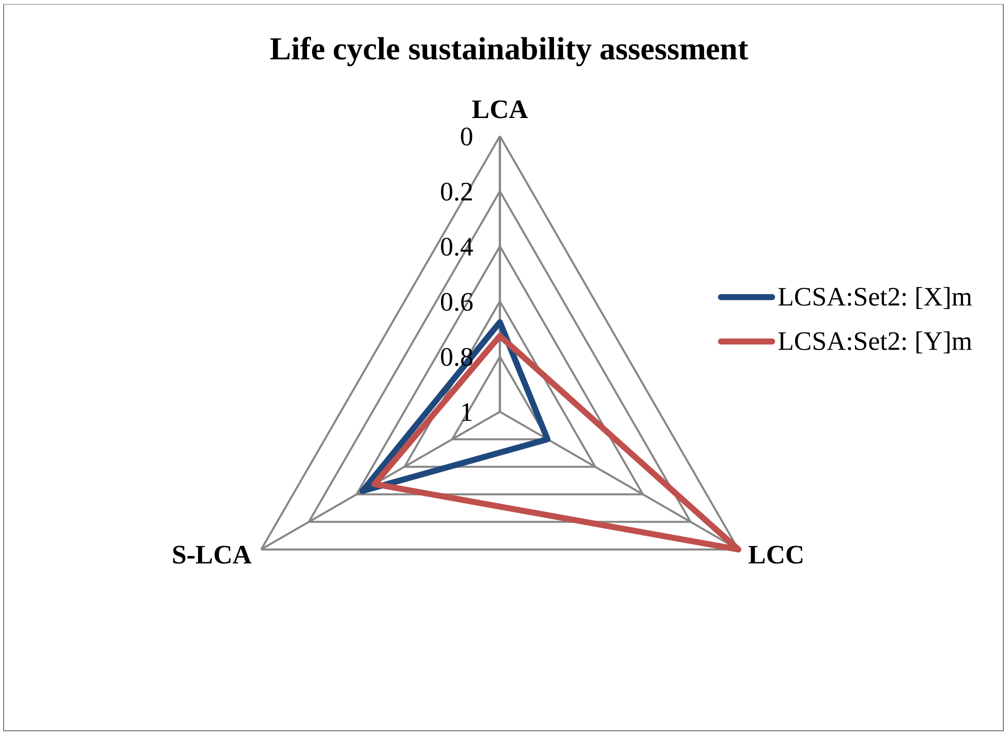

Figure 21.6: Comparison of sustainability performance of biomethane and biohydrogen produced from OFMSW for application in electricity generation processes.

The economic performance of the biomethane technology for biomethane use in the electricity generation systems records the highest economic performance value of 0.80. Unfortunately, the application of the biohydrogen technology for the electricity generation in the urban settings is economically unsustainable. The economic performance of the application of biomethane in electricity generation systems has the net present value (NPV), internal rate of return (IRR) and payback period (PBP) of 4.67, 17.12% and 4.14, respectively. While, the application of biohydrogen technology in the electricity generation systems is unsustainable. The biohydrogen faces several bottlenecks, largely related to the biohydrogen production efficiency in the thermophilic dark fermentation process. The fact is that the production yields of the biohydrogen technology do play a crucial role in determining the economic performance of the technology. Again, the poor economic performance is also influenced by both the collection and transportation of the OFMSW. There is a need to improve the logistics around the collection and transportation of the OFMSW in order to achieve the reduced economic costs associated with the collection and transport of the gaseous biofuels. The high economic performance is largely influenced by the thermophilic dark fermentation process which is coupled with high energy inputs but low energy output due to low production efficiencies of the biohydrogen technology.

The social aspects is the least performing dimension of sustainability for the case of the application of gaseous biofuels in the electricity generation systems among the other three dimension of sustainability in the application of biomethane in the electricity generation systems. It can be seen that the economic aspects perform better when compared to the other dimension of sustainability with the value of 0.80, and followed by 0.68 and 0.43 which represent the performance value for the environmental and social aspects, respectively. The social aspects consider the availability of resources and human skill capacity to operate the biogas digesters urban areas. It was observed that there is a need for the management of the biodigester system by well-trained technicians. In certain cases the digester may be non-functional due to broken parts of the digester. Therefore, it is imperative to have day-to-day operations to manage the digester operations by well-trained technicians. The success of a particular energy technology not only depends on the financial viability but also takes into account the social consideration among the different stakeholders. The social aspect is one of the equally important dimension of sustainability and needs to be taken into account for the implementation of the sustainable energy infrastructural development.

6.2. Biomethane versus biohydrogen comparison in vehicle operation

The urban setting has a great demand for the transportation fuels for vehicles. This section discusses the comparison of the sustainability performance of the application of biomethane versus biohydrogen in the vehicles operations. Figure 22.6 shows that the use of the biomethane in the compressive natural gas vehicles (CNGV) is more sustainable when compared to the use of the biohydrogen in the fuel cell vehicles (FCV). The CNG vehicles record the sustainability performance index value of 1.83, while the FC vehicles record the value of 1.35, respectively. It can clearly be seen that the application of biohydrogen in the FC vehicles is economically unsustainable, which presents the challenges for the implementation of the biohydrogen technology in the urban settings for the vehicles operations.

It can be noted that the economic performance plays a crucial role to influence the sustainability performance of the gaseous biofuels in the vehicles operations. The application of biomethane in the vehicle operations considered the following economic indicators, i.e. the net present value (NPV), internal rate of return (IRR) and the payback period (PBP), which records the values of 4.44, 16.63% and 4.13, respectively. The installation infrastructural development of the biomethane technology for use in CNG vehicles is economically profitable, which provides an opportunity to recover the investment made on the project. The economic performance of the biomethane technology in the vehicles operation is economical attractive and should be pursued for the installation in the urban areas. The high net present value indicates that the project in terms of benefit and cost of infrastructural stands on the better opportunity to make profit. Therefore, it is believed that sound economic performance of the installation gaseous biofuels infrastructural development will encourage people to install these technologies in the urban settings.

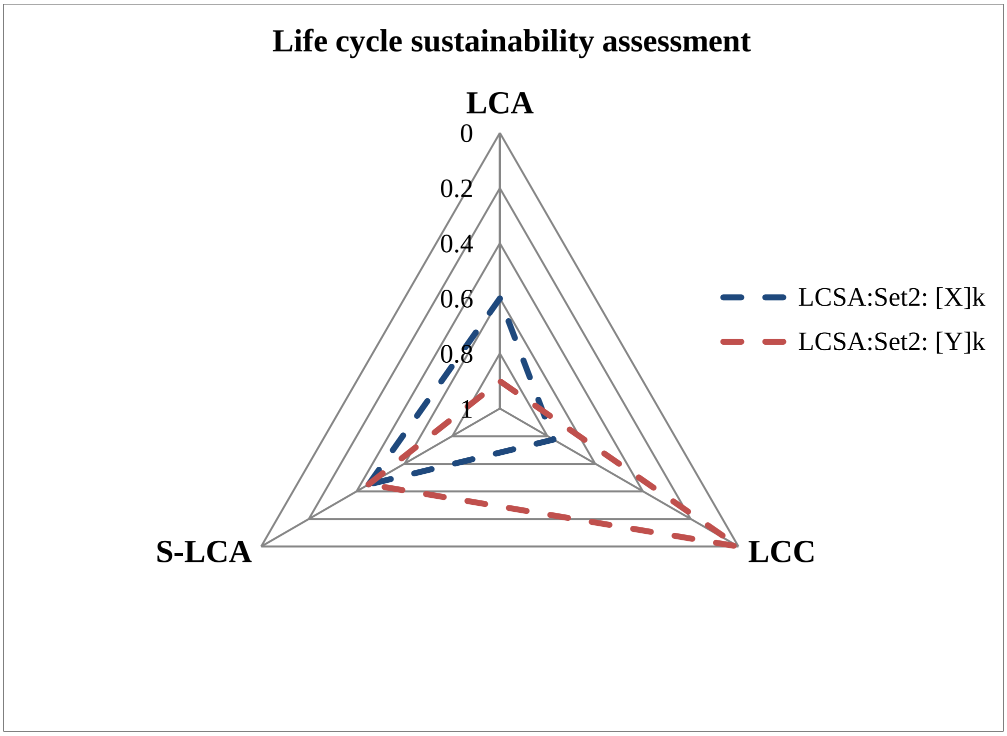

Figure 22.6: Comparison of sustainability performance of biomethane and biohydrogen produced from OFMSW for application in vehicle operation.

The urbanization is expected to increase over the coming years due to the fact that people will be moving from one location to the other for opportunities and economic reasons. The urbanization is expected to increase the organic fraction of municipal solid waste (OFMSW) streams generated in local areas around the major cities. This presents an opportunity for increasing in the installation of the biogas digester systems. The biogas sector is growing and maturing in South Africa and it is expected that various stakeholders will be established in the coming years. One of the stakeholders, the industrial companies, are starting to own intellectual rights (IP's) of various types of biodigester systems. These digester systems come in different sizes and operational procedures suitable for the installation in the urban settings. It is no doubt that the industrial companies are expected to benefit based on the design, installation and maintenance of the biogas infrastructural development in the urban settings. In the urban settings the installation of the biogas digester systems requires approval from local municipal authorities. Many of the biogas digester systems in the urban settings are installed by private companies. The private companies hire and train staff for the installation and servicing the installed biogas systems in the urban settings.

In urban settings it was observed that the biogas systems require operation and maintenance by the trained personnel. The challenge in the urban settings is the fact that people move from one location to the other for economic opportunities. In the process, the well-trained technical skills for the operation of the biogas infrastructural development are quickly lost in this geographical setting. In certain cases the biogas infrastructural development is left non-operational because of the lack of the trained skilled personnel to operate and maintain the biogas infrastructural development. The operation and maintenance of the biogas infrastructural development in the urban areas require a well-trained technician with education background to operate the digester system.

The urban setting is easily accessible and several research groups conduct research for the biogas production and implementation. This is attractive because further educational knowledge is provided for the successful implementation of the sustainable energy generation systems, such as biogas systems. The installation of the biomethane technology is attractive, especially for the operation of the vehicles in this geographical location. The urban setting has a great demand for transportation fuels to transport people and products within the surrounding areas. The use of biohydrogen as the fuel for the transportation vehicles is unsustainable and largely influenced by the negative economic performance. However, it must be emphasized that the biohydrogen technology still has the potential for vehicle operation as long the economic performance can be improved and reduced to sustainable outcome. Finally, the urban setting must maintain the technical skill for the installation and operation of the innovative infrastructural development for the biohydrogen technology.

6.3. Biomethane comparison in electricity generation versus vehicles operations

The urban setting has demand for both electricity and vehicle fuel. The results for the sustainability performance of the use of biomethane in electricity generation versus vehicles operations are presented in this section. Figure 23.6 shows that the sustainability performance index (SPI) value of the use of biomethane in combined heat and power (CHP) systems is slightly higher when compared to the use of biomethane in compresses natural gas (CNG) vehicles. The results of the SPI value for the electricity generation in the CHP systems stands at 1.90, while the CNG vehicles records the value of 1.83. This outcome indicates that organic municipal solid waste (OFMSW) provides a very strong case for admission of biomethane for production of both the electricity generation and also as vehicle fuel. In fact, the use of the biomethane will strongly depend on demand for a particular fuel (either for electricity generation or as fuels for vehicles).

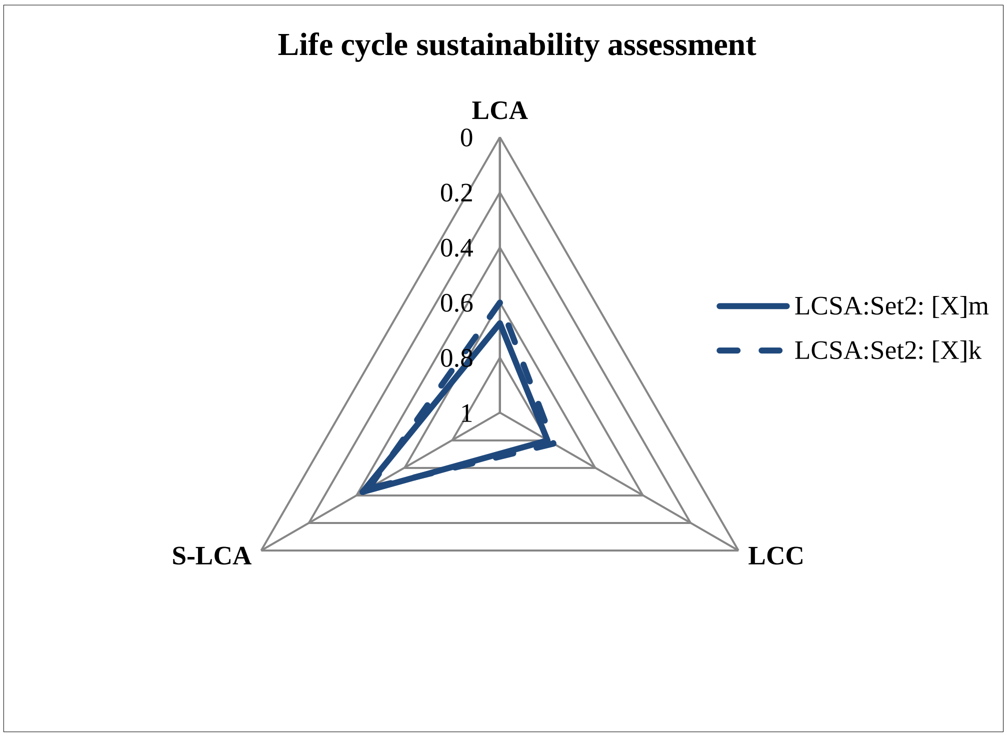

Figure 23.6: Comparison of biomethane produced from OFMSW for both applications in the electricity generation processes and also in vehicle operation.

The use of the biogas technology results in increased biogas production efficiency and this improves the economic performance of the digester system. In order to achieve high biogas production efficiencies, the digester requires skilled technicians to improve the operational conditions of the biodigester. In certain instances, the production efficiency of the biodigester can be achieved through the biodigester design, which ensures that maximum production efficiency is reached during the biodigester operation. It is important to point out that the application of biomethane is economically feasible and is the most sustainable among the three dimension of sustainability. It must be emphasized that production efficiency is very important for the economic aspects of the biodigester. Increasing the biodigester production efficiency achieves sound economic performance of the biodigester system.

The OFMSW is a waste-based residue that can be used for the generation of electricity or energy fuels for vehicles. The harvesting or collection of organic waste-based residues for gaseous biofuel production remains a societal challenge for many communities. There is a need to establish and educate various stakeholders in order to drive the bioenergy technologies towards more sustainable production. In urban setting the quality of collected feedstock is affected by the way it is collected and is often affected at the point of collection. In terms of life cycle thinking communities needs serious education exposure about taking an initiation in selection of feasible feedstock for bioenergy production. The education level plays an important role because it informs people about the status of affairs regarding the energy systems of the country and also their role in ensuring the energy security for future generations. The people in urban areas with awareness and knowledge about the status of energy need to move towards better energy production systems which are environmentally sustainable.

Education plays an important role because when people are aware of the energy challenges the country is facing they take initiative steps to address the problems. The level of education exposure makes room for creativity and application of innovative solutions because of the better education level of the people in the urban areas. Urban areas seem to be the place of innovative energy generation because of the education level of the people, who often seek opportunities to implement innovative solutions to address the shortage of energy systems. The implementation of the new biogas infrastructural development faces several challenges, including the breakdown of the biodigester system. The people in urban areas have technical ability to spot and fix a bioreactor system at the earliest stage in order to improve the production efficiencies of the bioreactor system. The urban setting has easy access to human skill and services which is a great requirement for the installation and operation of the biogas digester systems. The stakeholder groups in urban areas are well connected and often work together in one way or the other. The urban setting is located very close to research centers and academic institutions, and the results show that educational training and availability of information and knowledge are easily accessible in urban areas. The fact that the human skill capacity is accessible promotes easy accessibility of the installation of the renewable energy technologies such as biogas infrastructural development.

6.4. Biohydrogen comparison in electricity generation versus vehicle operation

This section discusses the sustainability comparison of the application of biohydrogen in the electricity generation systems versus vehicles operations. Figure 24.6 shows that the comparisons of the biohydrogen application for both the electricity and vehicle operations. The application of the biohydrogen in the vehicle operations offers high sustainability performance outcome when compared to the electricity generation systems. The use of biohydrogen as the fuel for vehicle operation records high sustainability performance index value of 1.35, while the electricity generation in the FC systems records the SPI value of 1.20. The results of this study indicate that the application of biohydrogen in both cases for electricity generation and vehicles operation is economically unstainable. Based on the graphs, the negative in the overall sustainability performance is the economic aspect which is unsustainable for both cases of the fuel-end use – see Figure 24.6.

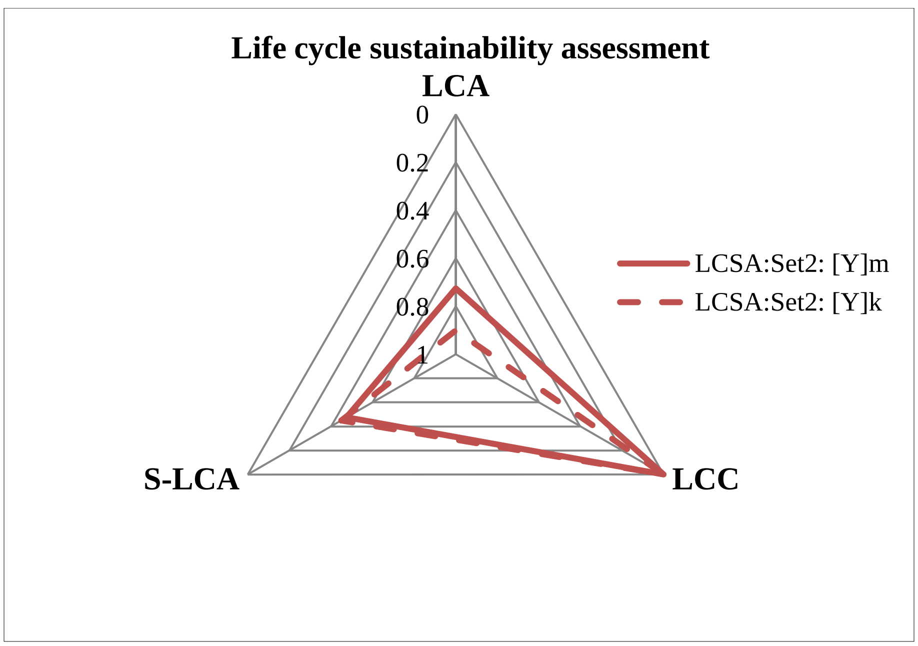

Figure 24.6: Application of biohydrogen produced from OFMSW for both applications in the electricity generation processes and also in vehicle operation.

The biohydrogen technology is economically unsustainable, thus affecting the sustainability of the production and application of the biohydrogen in the electricity generation and vehicles operations. For the case of social and environmental dimension, the sustainability performance outcome is promising for both cases for the production and application of biohydrogen in the electricity generation systems and vehicles operations. In comparison, among the three dimension of sustainability the application of biohydrogen in fuel cell (FC) systems offers higher social benefits when compared to the application of biohydrogen in fuel cell (FC) vehicles for the case of urban settings. While, the social performance is virtually the same for application of the biohydrogen in the FC systems and CNG vehicles. Unfortunately, the biohydrogen technology application in urban settings should be rejected due to the poor economic performance of the study cases.

The urban setting is a geographical location consisting of attractive economic activities for the installation of innovative energy generation systems. It is expected that the installation of the innovative digester systems will increase in urban settings. This provides the opportunity for the installation of new innovative energy-generation infrastructural development. It is important to install energy generation systems that are economical feasible in order to achieve the sustainable performance of the gaseous biofuel implementation in the urban settings. Not only does the installation of the energy generation infrastructural development provide the much-needed energy, but also results in the reduction of the accumulation of OFMSW in waste landfill sites.

7. CHAPTER 7: DISCUSSION OF THE RESULTS FOR THE LIFE CYCLE SUSTAINABILITY ASSESSMENT OF A RURAL SETTING

7.1. Biomethane versus biohydrogen comparison in electricity generation

This section discusses the sustainability performance of the production and application of gaseous biofuels (i.e. biomethane and biohydrogen) that are produced from cattle manure, with special focus on the rural settings. Figure 25.7 shows that the use of biomethane in a combined heat and power (CHP) system for electricity generation commands the highest sustainable performance index value of 1.75, when compared to biohydrogen application in fuel cell (FC) systems for electricity generation, which stands at 1.03. The biomethane technology offers the most sustainability performance when compared to the biohydrogen technology for the electricity production in rural settings. The results indicate that the biohydrogen technology is mostly influenced by the worst economic performance when compared to the biomethane technology. Actually, the biohydrogen technology for the electricity generation in the rural settings is unsustainable. Among the three dimension of sustainability environmental aspects contribute to higher sustainability performance when compared to other dimension of sustainability such as economic and social aspects, respectively.

The use of the biomethane produced from 1 kg volatile solids (VS) cattle manure in electricity generation favors the biomethane process with the electrical energy of 0.64 MJ/kg VS, while the biohydrogen technology gives the electrical energy of 0.19 MJ/kg VS. The term “sustainability” advocates effective utilization of resources. In this case, the use of cattle manure for electricity generation in rural areas plays an important role in determining the overall sustainability performance. The biomethane technology requires less utilization of cattle manure volumes to achieve the high output of electrical energy of 0.64 MJ/kg VS, while the biohydrogen technology to achieve this electrical energy output will require more utilization of the cattle manure volumes. The sustainability performance is influenced by the volume of the cattle manure that is processed for the electricity generation. It is important to note that the cattle manure volumes influence all the three dimension of sustainability (environmental, economic and social).

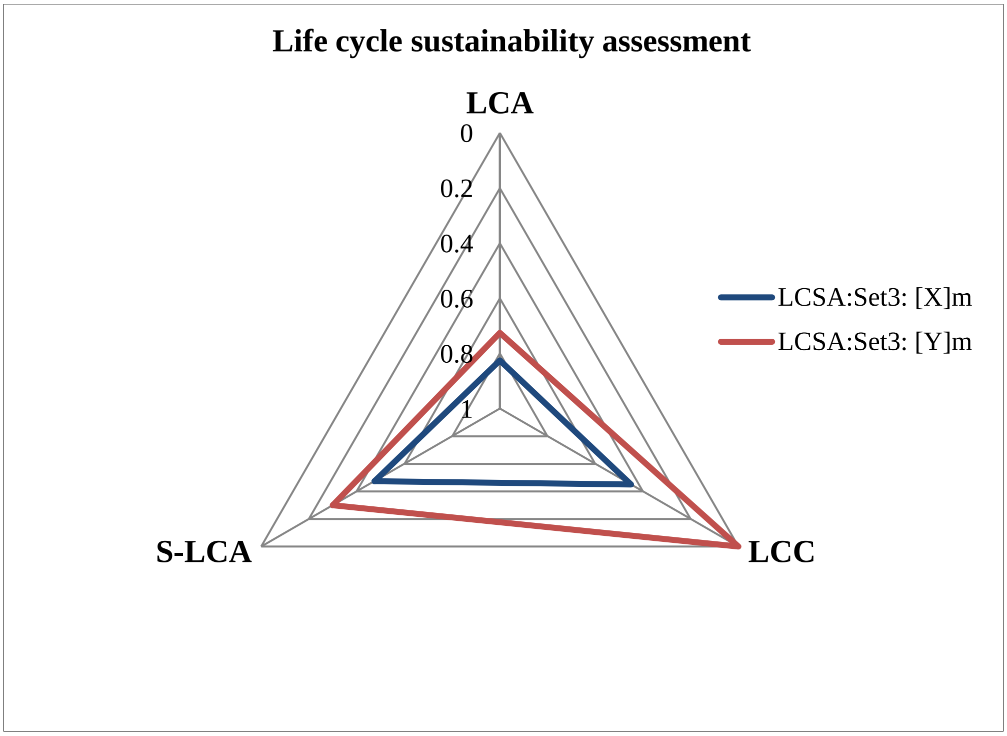

Figure 25.7: Comparison of sustainability performance of biomethane and biohydrogen produced from cattle manure for application in electricity generation processes.

The biomethane technology results in the increased production efficiencies of the biomethane gas which influence the sustainability performance outcome of the technologies. Unfortunately, biohydrogen technology has low production efficiencies of biohydrogen while demanding high energy and chemical inputs for the thermophilic fermentation. The low productivities of the bioprocess worsen the environmental and economic performance of the biohydrogen technology. Again, the disadvantage of the biohydrogen technology is the fact that the technology demands high chemical and energy inputs, while producing the electrical energy outputs when compared to the biomethane technology. The biohydrogen technology commands the worst economic performance, thus rendering the technology unsustainable for the electricity generation in the rural settings.

The installation of the infrastructural development for gaseous biofuels production and application in the rural settings creates economic opportunities for the local people. The biomethane technology records the most sustainability performance index value of 1.75, when compared to biohydrogen technology with the values of 1.03. The rural setting is a geographical location which is mostly suitable for the installation of the biomethane infrastructural development. The rural areas face several challenges such as shortage of trained skilled technicians for both installations and operation of the energy generation technologies. However, the local people in rural settings take opportunities presented through various workshops and training programs, taking take full ownership of the installation and operation of the biomethane energy infrastructural systems.

It is therefore clear that the installation of the biomethane creates low-skilled employment for the local people in rural settings for both installation and operation of the biodigester systems. It also provides them with much-needed energy for cooking and heating purposes. The installation of the biomethane technology in the rural settings has strong connections in changing the lives of the local people by providing the needed energy fuels and also providing job opportunities. It was noted that various stakeholder engagements in the rural settings play a critical role to the successful installation and operation of the new energy infrastructural development. It was observed that if proper consultation with various stakeholders is not followed correctly, the project can come to halt and become non-functional. There is a need for proper consultation with various stakeholder groups, including community leaders, about the plans to implement the new energy generation technology.

The biomethane technology shows sustainability due to the fact that the technology can be better managed and operated in the rural settings in the case of the application of the gaseous biofuels in the electricity generation systems, when compared to the biohydrogen technology which requires highly skilled technicians. The biomethane technology can easily be installed and operated using various digester designs which are adaptable for the implementation in rural settings, while the biohydrogen technology requires sophisticated biodigester design. This is due to the production pathway of the biohydrogen which requires carefully operational conditions for the production of biohydrogen in the biodigester systems. The social dimension plays a crucial role in the sustainability performance of energy generation systems. Actually, the biohydrogen technology is unsustainable for the installation and operation in the rural settings.

7.2. Biomethane versus biohydrogen comparison in vehicle operation

Regarding the results for the comparison of the biomethane technology versus biohydrogen technology for the gaseous biofuels application in vehicle operation, Figure 26.7 shows that biomethane application in compressed natural gas (CNG) vehicle operation performs better when compared to the use of biohydrogen in fuel cell (FC) vehicles. The application of biomethane in compressed natural gas vehicles records the most improved sustainability performance which stands at 1.68, while the biohydrogen application in FC vehicles stands at 1.10. Among the three dimension of sustainability, the biomethane application performs exceptionally well in economic aspects when compared to the biohydrogen aspect. These findings clearly indicate that biohydrogen application in vehicle operation needs further improvement in order to be comparable with those of biomethane applications.

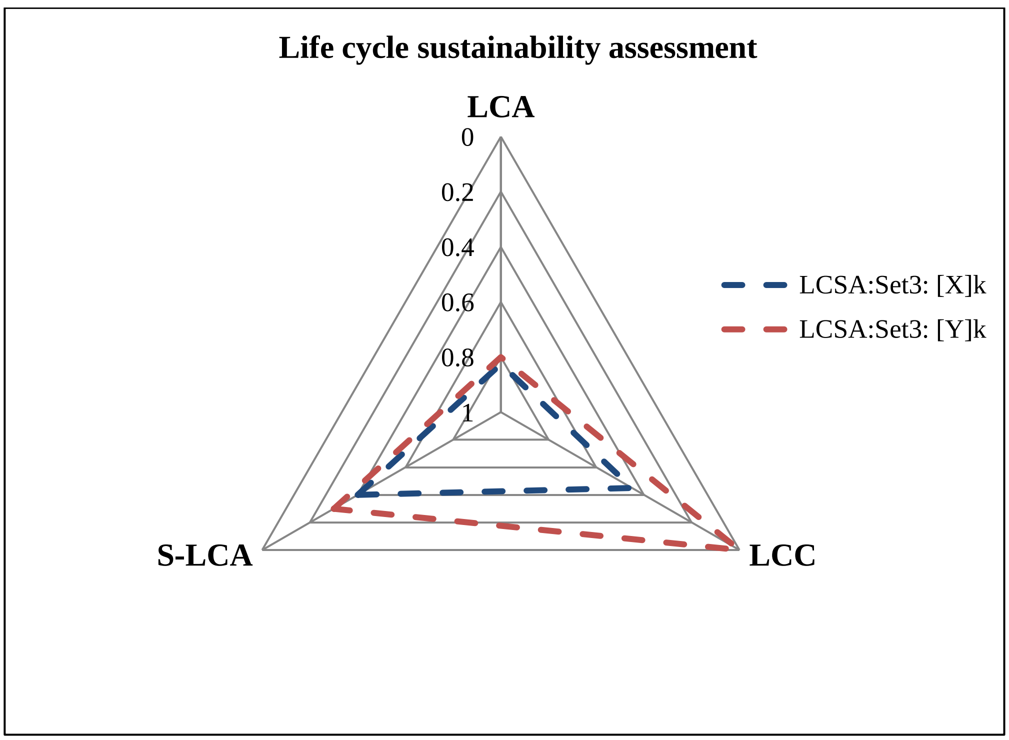

Figure 26.7: Comparison of sustainability performance index of biomethane and biohydrogen produced from cattle manure for application in vehicle operation.

The application of biohydrogen technology for vehicle operation in rural settings faces several challenges. The dark fermentation process is a very sophisticated technology and requires well-trained technicians for both installation and operation of the technology. In terms of operation of the technology the skilled technicians should be able to carefully manage the microbial growth and granulation within the digester system. The dark fermentation process requires formation of the bacterial granules which plays a crucial role in achieving high productivities. The digesters that have formed bacterial granules can be operated at high hydraulic retention time (HRT) without resulting in bacterial wash-out, which is important for the biohydrogen production process. During this generation process, the hydrogen partial pressure within the bioreactor should be maintained at a very low level in order to ensure effecting high productivities of the biohydrogen within the reactor system. The microbial species must form granules which assist in keeping high microbial species with the bioreactor. The bioreactor systems are operated at a high feeding rate and this often results in the bioreactor wash-out, thus reducing the microbial species within the biodigester. Therefore, maintaining appropriate hydrogen partial pressure within the reactor when using cattle manure as a feedstock for biohydrogen generation requires careful consideration when compared to biomethane production in the rural areas.

The social performance of the application of the biohydrogen in vehicle operation is largely influenced by the fact that the people in rural communities have the right attitude and take the responsibility of the energy generation technology. The rural setting lacks infrastructural development to service the sophisticated technology for the biohydrogen technology; however, there is extreme potential for the markets growth for new energy generation technologies. The rural areas are on the road towards growth as the services and new infrastructural systems are installed in there. It is important to note, however, that the implementation of the biohydrogen technology in the rural areas is unsustainable at the moment, for both cases of electricity generation and vehicle operation.

The biohydrogen technology shows reduced environmental emission in the application of biohydrogen in electricity generation options such as fuel cell (FC) systems. The use of biohydrogen in the combustion engines in the fuel cells results in the production of only water as the byproduct without releasing any carbon in the environment. In order to address the energy challenges, it is important to identify potential markets before implementing a particular technology in the geographical setting. The rural setting has great demand for an energy source for electricity generation, when compared to the demand for the transportation fuels. The rural setting faces serious challenges in terms of infrastructural development and capacity to service the biohydrogen technology. Therefore, one way to address the challenges is to consider carefully the demand of the particular fuel and its end-use in the specific geographical location. Furthermore, it is important to ensure the selection of sustainable energy production systems in the particular geographical location.

7.3. Biomethane comparison in electricity generation versus vehicle operation

This section presents the discussion of results for the application of biomethane produced from cattle manure for electricity generation versus vehicle operation in rural settings. Figure 27.7 shows that the electricity generation from biomethane records the higher sustainability performance index value of 1.75, when compared to vehicle operation, which records the value of 1.68. The biomethane technology is showing sustainability performance for both cases of biomethane application in electricity generation and vehicle operation. Therefore, the choice of biomethane use will depend on the fuels demand in the rural settings. It is important to realize that the rural setting has demand for both the electricity generation and vehicles fuels, especially the electricity generation systems. The biomethane technology achieves higher sustainability performance for environmental and economic dimension among the three dimension of sustainability.

In terms of economic performance, the application of biomethane is equally comparable and sustainable for both cases of biomethane application -- in electricity generation, and as transportation fuel. The application of biomethane in electricity generation has the highest net present value (NPV) of 1.26, when compared to vehicle operation, which records an NPV of 1.18. The biomethane application in the electricity generation records also a slightly higher internal rate of return (IRR) and the payback period (PBP) values of 1.59% and 6.22, respectively. For the case of biomethane application as fuel in natural gas vehicles, it records a slightly lower IRR and the PBP values of 12.36% and 6.15, respectively. The economic performance of the application of biomethane technology is economically viable for both cases of electricity generation and vehicle operations. However, it is important to mention that the type of energy demand determines the application of the technology in the rural areas. The end-use of the biomethane for both cases in the electricity generation and as transportation vehicle is almost equally sustainable for both cases in the rural settings. Therefore, it is important to realize the energy demand of the particular fuel will determine the choice of the technology implementation in a geographical location. The fuel application in the particular areas should be based on a decision around stakeholder engagement. Sustainability involves consideration of various stakeholder groups that facilitate better use of resources. Often, resources can be used, but sustainability promotes the consumption patterns that assist the present generation to utilize resources in a way that future generations will be able to use to meet their needs.

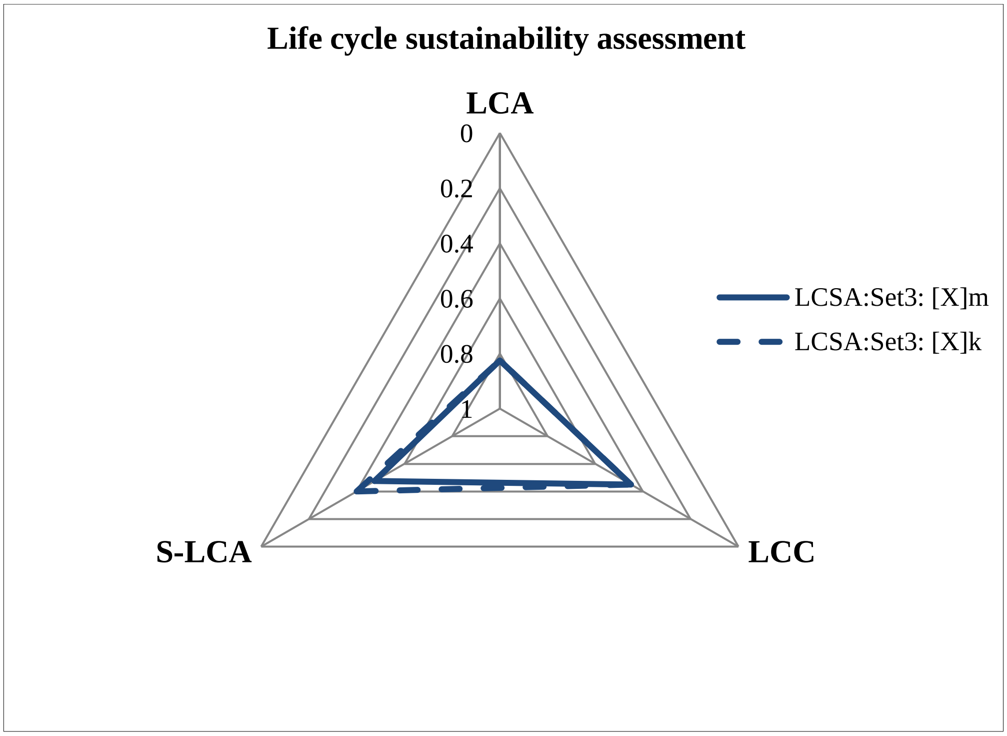

Figure 27.7: Comparison of biomethane produced from cattle manure for both applications in the electricity generation processes and also in vehicle operation.

There are several considerations that need to be taken into account when planning an implementation of the particular energy infrastructural development in the particular geographical setting. The choice of energy infrastructural development is influenced by several factors, such as technology type, fuel end-use, fuel demand, feedstock type, geographical settings, etc. It is important to mention that technology learning and new infrastructural implementation should also form part of sustainability development. There is strong demand of the implementation of the innovative technologies in order to advance the agenda for sustainable development in different geographical locations. In the light of the technology learning and development, it is important to realize that human resource for knowledge production is very important for advancing the innovation of the energy infrastructural development. The rural communities are faced with low levels of education background and skill capacities. The skill capacity in rural setting can be increased through learning and training programmes that are targeted to develop the procedures and systems necessary to sustain high performance of the technology.

At the moment it is very clear that the application of biomethane technology is both sustainable for the application in the electricity generation and also as the fuel for vehicles. The electricity generation provides the local households with much-needed energy for cooking and heating purposes. The intention of the installation of the biomethane technology for vehicle fuel is to provide energy generation options to build future sustainable networks. Again, the implementation of the biomethane as transportation fuel provides the opportunity for the technology learning in the rural areas. The government is promoting the blending of the fuels; the biomethane can be blended with the natural gas at various levels for the application in natural gas vehicles in rural settings. This has several benefits such as the policy of fuel levy incentives (yet to be revised to include biomethane). Furthermore, the installation of the biomethane technology for energy generation for transportation fuels is very important for the inventory data gathering in rural settings. This study clearly provides a guideline to the selection of energy infrastructural development and of potential options for the gaseous biofuels application in a particular geographical location.

7.4. Biohydrogen comparison in electricity generation versus vehicle operation

This section presents the discussion of the results for the comparison of the application of the biohydrogen in the electricity generation systems versus the use of the biohydrogen in vehicle operation. Figure 28.7 indicates that the biohydrogen production for application electricity generation systems and also as a transportation fuel is both unsustainable. It can be seen that the economic aspect commands the worst sustainability performance for both cases of the electricity generation and vehicles operations. It is important to realize that the application of the biohydrogen in vehicles operations record the sustainability performance index value of 1.10, which is higher than that of the biohydrogen application in electricity generations systems with the value of 1.03. These results indicate that the application of biohydrogen in the vehicles seem to offers better application in rural settings when compared to the electricity generation. This is very interesting, because the rural setting has greater demand for electricity generation than vehicle fuels. Therefore, the results demonstrate that the biohydrogen technology has the potential for application as the fuel for both electricity generation and also for vehicle operations. The choice of the biohydrogen application in the rural area will depend greatly on the energy demand, either fuel source for electricity generation or vehicle operation.

The implementation of the biohydrogen technology in the rural settings should take into account the availability of the infrastructural development to service the technology and the economic potential of the surrounding geographical setting. Actually, the installation of the energy infrastructural development is mostly subsidized and funded through government programs. The results of this study clearly demonstrate that the biohydrogen technology is unsustainable and should be rejected for the implementation in the rural settings. In the case of the biohydrogen technology, the production costs of biohydrogen are significantly higher with low productivities of the dark fermentation process. It is important to note that the operating cost is directly proportional to the hydrogen yield and the capital cost is directly proportional to the production rate.

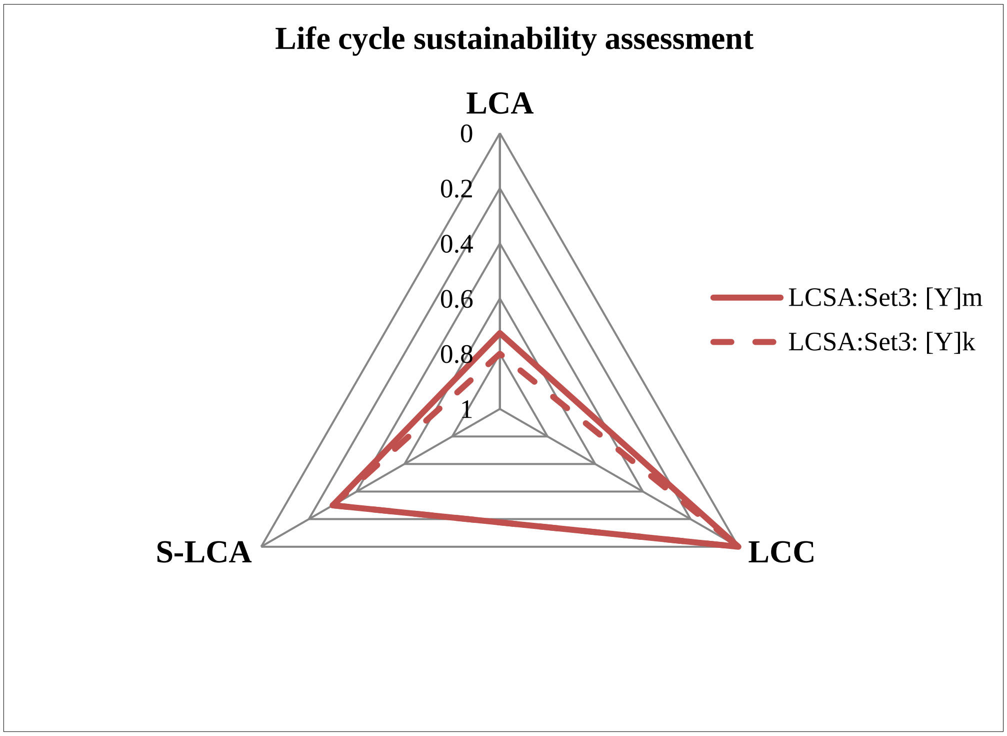

Figure 28.7: Comparison of biohydrogen produced from cattle manure for both applications in the electricity generation processes and also in vehicle operation.

The use of cattle manure as the feedstock for production of biohydrogen generation in the dark fermentation results in low biohydrogen yields (amount of the biogas and biohydrogen content). The thermophilic dark fermentation gives a hydrogen yield of 4 mol/mol glucose. But still the energy capture from glucose to hydrogen is only 33%. For most energy-generating processes, the energy balance is affected by the biogas production which influences the results for the digester performance. The conversion efficiency of the dark fermentation represents the starting point of energy profitability for the chosen feedstock. It is important to note that the production yields vary from one feedstock to the other depending on the characteristics of the organic residues. There is a need to increase the metabolic pathway for the thermophilic fermentation process. The results of this study indicate that the use of cattle manure is less suitable for the biohydrogen technology in the rural settings. Therefore, the use of the sustainability assessment approaches provides an opportunity for the selection of the sustainable energy infrastructural development.

8. CHAPTER 8: COMPARATIVE DISCUSSION ACROSS THE THREE DIFFERENT AFRICAN SETTINGS

The previous Chapters 5, 6 and 7 compared and discussed the sustainability performance of the biomethane versus biohydrogen option in each separate setting (i.e. brewery wastewater, OFMSW and cattle manure). Chapter 8 presents comparative discussions across the three different settings. Section 8.1 presents an overall comparison. Sections 8.2 and 8.3 discuss biomethane, for electricity and vehicle applications, respectively; sections 8.4 and 8.5 do the same for biohydrogen. Section 8.6 presents further notes on the method for the social LCA.

8.1. Biomethane and biohydrogen comparison in the three selected settings

At the moment there is a great demand for the energy resources for both electricity generation and transportation fuels. There are great opportunities in investing in alternative energy-generating technologies since in the future these are expected to play a crucial role. As has been reported in section 1.1.2, some of the renewable fuels might not be environmentally friendly; however, the production of renewable fuels from waste-based residues is seen as more promising than growing crops for the production of biofuels. According to published information on biogas yields (i.e. brewery wastewater, organic fraction of municipal solid waste (OFMSW), and cattle manure), biomethane achieves a significantly higher energetic yield than biohydrogen, at 9.0, 10.5 and 9.7 MJ/kg of VS. The organic fraction of municipal solid waste (OFMSW) seems to achieve a significant higher energetic yield and followed by cattle manure and brewery wastewater, respectively. Therefore, this study took efforts to determine the sustainability performance of the application of energy fuels produced from these different feedstocks. It considered the application of energy fuels in the application of the electricity generation systems and also vehicles operations. It is important to mention that the attractiveness to these feedstocks is their availability seasonally in different locations.

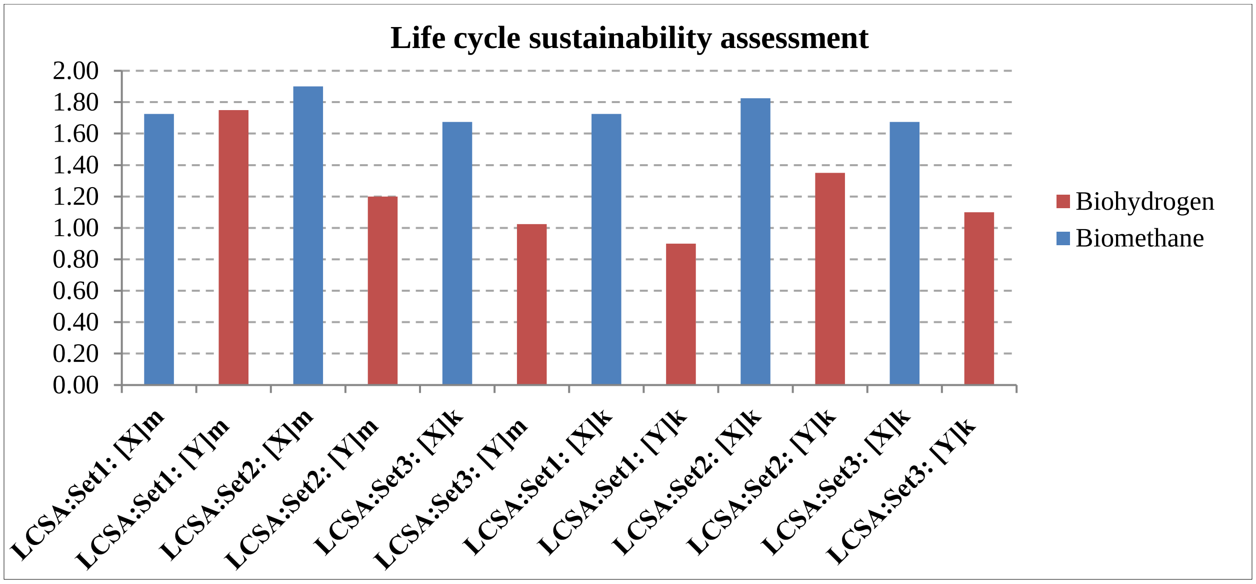

Figure 29.8: Sustainability performance index values for the application of gaseous biofuels (i.e. biomethane and biohydrogen) produced in three different settings for both applications in electricity and vehicles operation scenarios. X and Y represent the biomethane and biohydrogen technologies, respectively; the application of the energy fuels in electricity generation and vehicles operation is represented by m and k, respectively.

The application of the gaseous biofuels (i.e. biomethane and biohydrogen) produced in the three study settings was performed. Figure 29.8 presents the results for the sustainability performance for the comparison of the study scenarios for both the application in the electricity generation and vehicles operation. As it stands the application of biomethane in electricity generations systems for the case of OFMSW offers higher sustainability performance index (SPI) value of 1.90, and then followed by both the cattle manure and brewery wastewater with the sustainability performance index (SPI) value of 1.75 and 1.73, respectively. While, the application of the biohydrogen in electricity generation systems results to higher SPI value of 1.75 in brewery wastewater, and both the OFMW and cattle manure results to the SPI value of 1.20 and 1.03, respectively. Clearly, the biomethane technology commands the highest sustainability performance when compared to the biohydrogen technology in all the three study settings. This means that the biomethane options outcompete the scenarios of biohydrogen application in both electricity generation and also in vehicle operation. However, biohydrogen is showing great promise for application in agro-industrial settings, followed by the urban and rural settings for the application of gaseous biofuels in electricity generation systems and vehicles operations. Therefore, the biohydrogen technology should be slowly introduced for electricity generation in agro-industrial settings. However, it must be emphasized that at present, the sustainability performance of the biomethane technology outcompetes those of biohydrogen technology in both the urban and rural settings.

In this study, the sensitivity analysis was conducted for all the study scenarios generated in this study and the life cycle sustainability assessment (LCSA) results are shown in Appendix 12. Clearly, the sensitivity analysis results indicate that the varying in percentage levels had no effect on the outcome of the sustainability performance index (SPI) values. This is the demonstration of the sound and stability of the LCSA results generated in this study. However, it was observed that the sustainability performance index values are affected by the geographical location and the type of impact indicators in the particular settings. Therefore, each geographical location can be affected can be affected by a choice of impacts indicators that are considered during the life cycle sustainability assessment. However, it is important to state that the developed methodological approach towards sustainability assessment is quite stable and reliable across all the study scenarios investigated in this study.

8.2. Biomethane comparison for electricity generation in the three different settings

This section presents the results for the comparison of the biomethane application in electricity generation for the three study settings. Figure 30.8 indicates that the urban setting has the highest sustainability performance index (SPI) value of 1.90, followed by the rural and agro-industrial settings which consist of SPI values of 1.75 and 1.73, respectively. The urban setting is better suited for the infrastructural development for the biomethane technology, especially the application of the biomethane energy carrier in the electricity generation systems. In fact, the application of biomethane is showing competitive sustainability performance in all the three settings (i.e. urban, rural, and agro-industrial settings) that have been compared in this study. The biomethane technology faces no technical challenges for commercial application as there are already existing infrastructural development for the biomethane production and application across the three different settings. However, the technical feasibility application of the biomethane in terms of sustainability at different settings has not been explored. This study provides some of the insights into infrastructural development of the biomethane technology in different geographical locations.

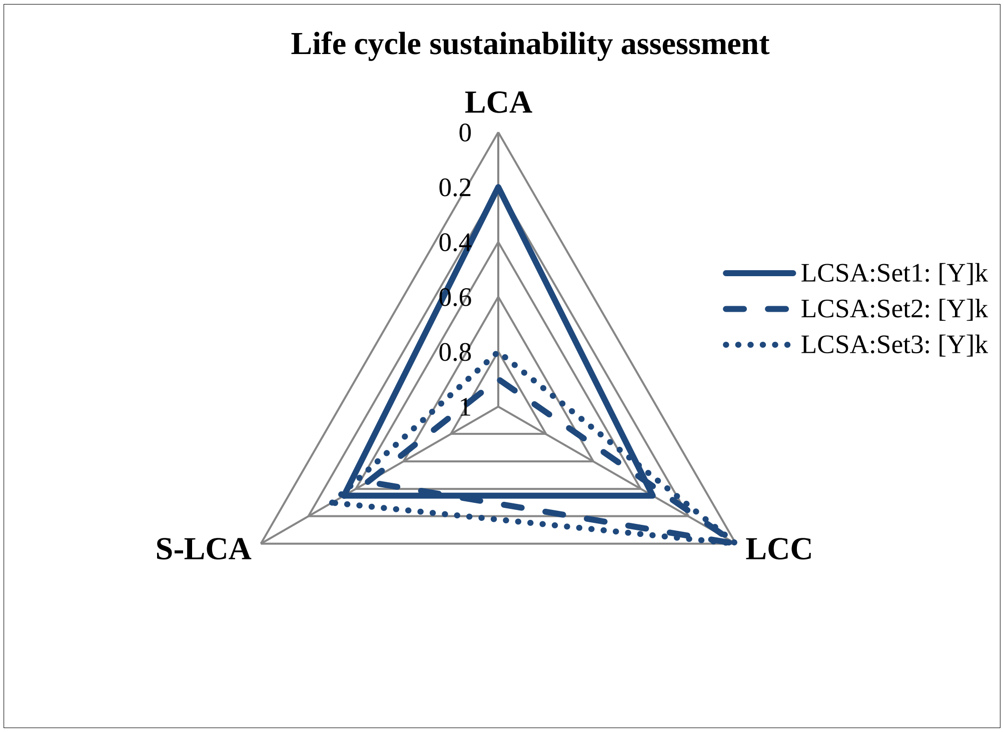

Figure 30.8: Sustainability performance of the application of biomethane for electricity generation in the three different settings.

The results of this study demonstrate that the social aspect plays a crucial role to influence the sustainability performance of the biomethane technology in the three different settings. The results of this study indicate that the application of biomethane in the combined heat and power (CHP) system for the rural settings improves the social performance by the value of 0.48. While, the scenarios for the urban and agro-industrial settings results to the social performance value of 0.43 and 0.38, respectively. For the case of the rural settings, the social performance resulted in the improved community livelihood whereby the local community had deeper social interaction with the installed biomethane technology. In the rural areas, the installation of biomethane technology requires a well-structured strategy and consideration that involves different stakeholders within the local community where the technology is installed. For example, the installation of the biomethane technology infrastructural technology in rural settings required the approval of local chiefs and key elders from the community. The installation of the biomethane infrastructural development resulted in job creation whereby local people where employed during construction and operation of the installed energy generation technology. The challenge in the rural setting is marked with the low level of education background and unavailability of technical skills. This can be addressed by conducting various forms of skills and development programmes that are aimed at building enough capacity for the installation and operation of the biomethane infrastructural development. It is important to highlight that in the rural settings, local people take ownership of the operation of the energy generation technologies, and there is interest among local people to undergo skills and training programmes. These programmes are very important and critical in the rural settings in order to ensure successful installations of the energy generation technologies. Therefore, the installation of the biogas infrastructural development has had direct social impact and improved the livelihoods of the local community by providing the much needed energy for cooking purposes. Furthermore, the installation of energy generation technologies improved the lives of the local people since many were still uneducated and unemployed.

It was observed in urban settings, that even though the biomethane infrastructural development was available, the people still did not utilize it to the maximum level. In terms of the urban setting, it was very difficult to monitor the direct impact of the biogas infrastructural development because there was a change in dynamics of the persons engaged with the technology. In this setting it was difficult to track the social impacts of the technology because of people movement and flows during the life time of the technology. The urban setting has a great movement of people from one place to the other within the geographical location in search of economic opportunities. This made it hard to track the meaningful impact of the technology that it had on their lives. However, the technology had impact on the providing the much-needed energy fuel for cooking and heating purposes. There is a need to put control measures in place to ensure that the skilled persons are retained in this setting in order to advance the biogas development geographical location. The urban setting is marked with access to informed and skilled persons to drive the innovation of the biogas infrastructural development. Finally, this setting is better located to access services and supply chain to support the installation and operation of the biogas infrastructural development for the local communities.

The sustainability considers the evaluation of three dimension of sustainability holistically (i.e. environment, economic, and social aspect). These dimensions have equal opportunity to influence the sustainability performance, depending on the geographical locations where the technology is inserted in the particular geographical location. For the case of the application of biomethane in the electricity generation, the results show that the sustainability performance in all the study settings is sustainable. Actually, among the three dimension of sustainability the environmental performance outcome contributes towards higher achievement of sustainability performance and followed by economic and social aspects for all the study cases. The rural settings reflect the most sustainable performance for the dimension of sustainability when compared to the other settings for the case of the application of biomethane in electricity generation systems. This is the reflection of the benefit that the installation of the biomethane technology will have great social benefit for the local communities in the rural settings, while in the agro-industrial settings the biomethane infrastructural development was mechanized and employed persons with high technical skills for the operation of the biogas infrastructural development.

The assessment of social impacts considers very broad sets of indicators, for example this study considered the following social indicators: availability of resource, community engagement, knowledge and skill development, safe and healthy living conditions, consumer savings, responsibility of the technology, existence of infrastructure for the technology, health and safety regulations, energy efficiency of the technology. As with all progressive instruments to measure the social aspect, the social life cycle assessment was successfully used to measure the social impacts within the context of the life cycle sustainability assessment (LCSA). The results of this study indicate that the rural setting offers the most sustainable social performance when compared to the other settings which are under the investigation in this study. The social impacts in rural setting is associated with the improvement in the livelihoods of people through creation of low-paying job opportunities, while the agro-industrial setting is industrial employing highly skilled technicians to support both the installation and operation of the biomethane infrastructural development.

8.3. Biomethane comparison for vehicle operation in three different settings

Figure 31.8 shows the application of biomethane produced from three different waste-based residues in compressed natural gas vehicles (CNG vehicle). The results demonstrate that the application of biomethane produced from OFMSW commands the highest sustainability performance which stands at 1.83, while those of agro-industrial and cattle manure report the sustainability performance index (SPI) value of 1.73 and 1.68. It is important to point out that the application of biomethane produced from OFMSW in the vehicles operation has the highest sustainability performance outcome when compared to the other two setting, namely: the urban and the rural settings, respectively. The use of biomethane as fuels for vehicles addresses many challenges related to the shortage of vehicles fuels in the urban and agro-industrial settings.

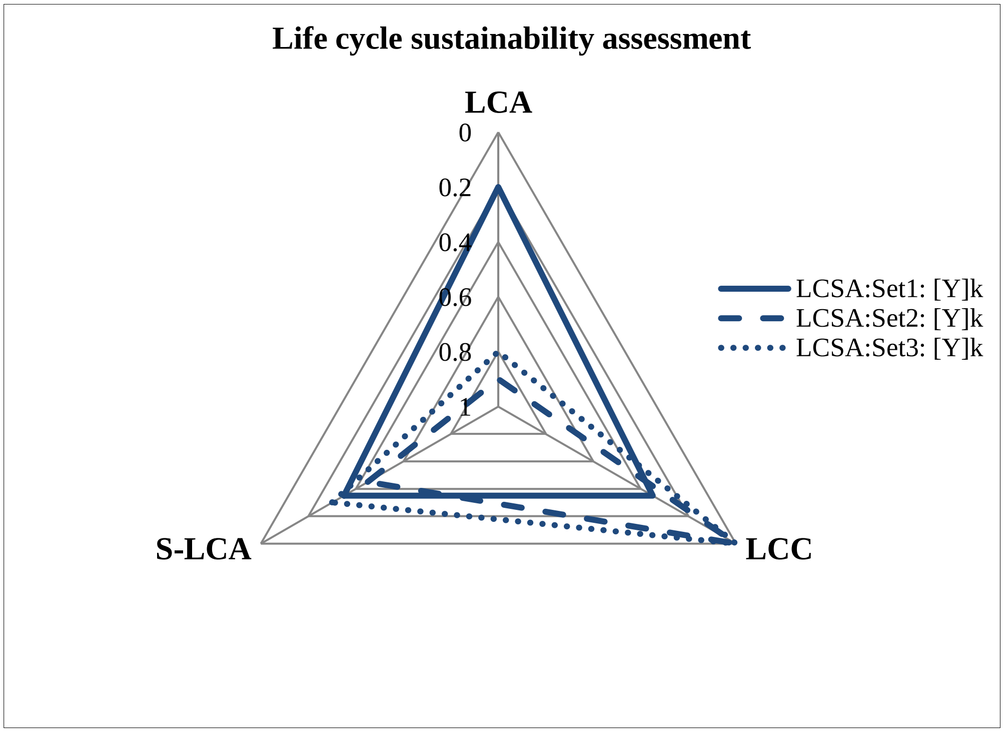

Figure 31.8: Comparison of sustainability performance of the application of biomethane in vehicles for three different settings.

It can be seen that the application of biomethane in the CNG vehicles is sustainable in all the three study settings. The rural setting improve the environmental performance by 0.83, while the agro-industrial setting report the environmental performance value of 0,68 and followed by the urban settings with the value of 0.60, respectively. In case of the use of biomethane as a fuel for CNG vehicles the results show that the rural settings will have a direct impact by the reduction of the environmental impacts. There is a great demand for alternative fuels for vehicles, not only for energy use but also to secure the security of environmentally friendly energy fuels. It is important to highlight that the three settings differs in terms of economic outlook which play a role to support services for the infrastructural development of biomethane technology.

In the case of the economic performance, the application of biomethane as a fuel for vehicles operation has the highest economic performance whereby the economic performance value records 0.78 in the urban settings, while the agro-industrial and rural settings report the economic performance value of 0.60 and 0.45, respectively. The application of biomethane in CNG vehicles is showing excellent economic performance in the urban settings when compared to those of agro-industrial and rural settings. The results of this study demonstrate that the excellent sustainability experienced in urban settings is also influenced by the economic dimension when compared with the other settings. The urban setting provide an opportunity for the investment in the infrastructural development for the application of CNG vehicles when compared to other settings.

The social performance for the application of biomethane in the CNG vehicles has virtually the same impact performance for all the three study settings (i.e. agro-industrial, urban and rural settings). For example the agro-industrial setting record the social performance value of 0.45, the same as urban setting with the value of 0.45, and lastly the rural setting records the lowest social impact performance value of 0.40. The results demonstrate that the application of biomethane in the vehicles has a competitive outcome with the social performance in all the three study settings. However, the local communities in the rural settings are unskilled and lack the necessary education background to manage and operate sophisticated technologies. The rural setting is the geographical location with lack to services and infrastructural development. The implementation of the CNG vehicles might be challenging due to the shortage of services to support the installation and operation of the technology. Therefore, this study highlights areas whereby the biomethane technology can be applied especially in the urban settings since the introduction of the CNG vehicles is sustainable. Finally, the results show that the intake of the CNG vehicles is sustainable for both settings in the agro-industrial setting, followed by the rural setting, respectively. The outcome of this study demonstrates that sophisticated technologies are useful and adaptable in the settings with the appropriate high skills for the innovation.

8.4. Biohydrogen comparison for the electricity generation in three different settings

Figure 32.8 indicates that the application of biohydrogen produced from brewery wastewater in fuel cells for electricity generation provides the most sustainable performance, which stands at 1.75. On the other hand both the urban and rural settings record the following sustainability performance values estimated at 1.20 and 1.03, respectively. The implementation of the biohydrogen technology for electricity production is suitable only in the agro-industrial settings. The biohydrogen technology is a very sophisticated technology that requires high technical skills for both the installation and operation energy infrastructural development. This setting has high energy demands for both electricity generation and also fuels for the vehicle operations.

The agro-industrial setting should be encouraged to install the biohydrogen infrastructural development. It has access to both the economic and human resource capacity for the installation and operation of sophisticated energy generation technologies. Advancing sustainable development production patterns will also assist the company to improve the way of doing their business. It has been observed that although the implementation of the biohydrogen technology in both the urban and rural settings is economically unsustainable, the economic performance of the energy generation technology is directly influenced by the production yields in terms energy per unit mass. As can be seen, the agro-industrial setting offers high energy yields, resulting in the improved economic performance in this setting.

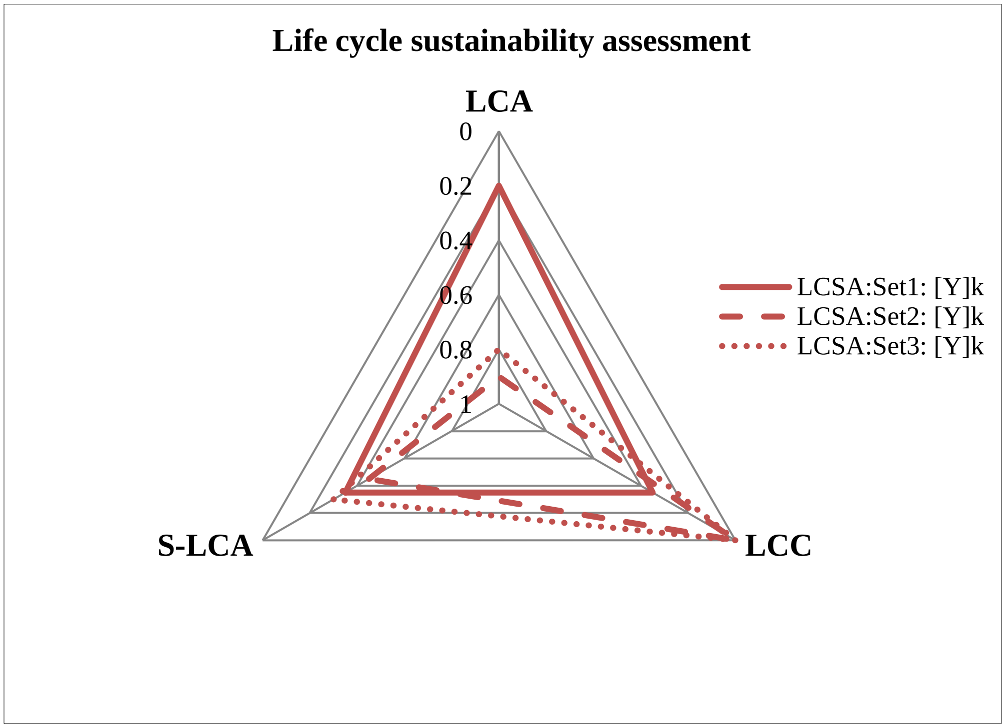

Figure 32.8: Comparison of sustainability performance of the application of biohydrogen in electricity generation system for the three different settings.

With regard to the environmental performance of the application of the biohydrogen produced from brewery wastewater in the electricity generation for the three settings, the application of the biohydrogen produced from the brewery wastewater commands the least sustainable environmental performance which record the value of 0.70, while both the OFMSW and cattle manure records equal environmental performance value of 0.73. Clearly, the study results show that the three study settings consists of the environmental performance outcome which is closely to each other. It is important to report that the environmental performance considers the emissions across the entire production and application of the gaseous biofuels (for example feedstock, collection, pretreatment, process, gas upgradation and application of the fuel). The agro-industrial setting consists of the geographical location that is suitable for the biohydrogen technology. It is important that the brewery wastewater requires minimum pretreatment approaches in terms of chemical demand before being channeled to the dark fermentation process. The pretreatment of both the OFMSW and cattle manure is complex and requires increased pretreatment requirements for digestion process. It is important that the environmental performance of the setting is greatly influenced during the production stages of the biofuels, rather than the application stages of the biohydrogen stages. The brewery wastewater seems to provide increased biohydrogen productivities when compared with the other two feedstocks. Finally, it is important that feedstock costs are significant and can render the technology application in the particular setting uneconomical.

The government has responsibility to drive and create necessary conditions for the introduction of the bioenergy technologies in the countries energy systems. The government can provide a necessary policy to drive the intake of the bioenergy systems by the industry. It can support various incentives such as carbon tax reduction for the operations that introduce bioenergy systems into mainstream energy utilization. In the case of the biohydrogen in the agro-industrial setting, the government can provide good policies and laws that promote the intake of the bioenergy systems. In rural settings, the energy infrastructural development is supported through various government support programs. The government has a role and responsibility to advance and support the implementation of the renewable energy technologies in order to achieve the sustainable development goals.

Industry is profit-driven and environmental policy-constrained. This best defines the agro-industrial setting whereby all of their operations need to improve their economic status while meeting all laws from authorities. Due to the increasing awareness of environmental concerns such as global warming and pressures from carbon tax policies, there is a shift in the industrial sector to find alternative production efficiencies that results in the minimization of the environmental impacts while achieving their profitability objectives. The socioeconomic status is one of the key factors that influence the new energy infrastructural development in a particular geographical region. Therefore, different geographical locations differ in the socioeconomic status. Figure 32.8 indicates that the social aspects of the three study settings favour the electricity generation from OFMSW in urban settings. The application of biohydrogen produced from OFMSW in fuel cells for electricity generation provides the most sustainable social performance which stands at 0.48. While the agro-industrial and rural settings record the social performance value of 0.40 and 0.30, respectively. In terms of the socioeconomic status it is important that settings with high income are set to benefit from the installation of advanced energy infrastructural development such as biohydrogen technology. For example, the agro-industrial setting has access to high-income status and can advance the installation of the infrastructural development for biohydrogen technology. It is important to highlight that in the agro-industrial settings the social benefits will be supported through creation of highly skilled technical jobs.

The results demonstrate that the installation of the biohydrogen technology in the agro-industrial settings has sustainable socioeconomic status that is able to create job opportunities. It is imperative to note that the installation of new energy generation technologies such as biohydrogen does not destroy the existing jobs in the energy sector, but creates new ones. This is very important because there is a high demand for sustainable job creation. However, the agro-industrial setting requires highly skilled technicians for the installation and operation of the sophisticated energy-generating technologies. Hydrogen is believed to be the energy carrier of the future; it requires a great deal of innovation and research development as the technology is still immature at the moment. There is great demand for the technology to improve the productivities so that the technology can be competitive with those of biomethane technology. Therefore, the installation of biohydrogen technology in the agro-industrial setting will take advantage of the access to human skills and also economic power in this setting.

The agro-industrial setting has both the economic potential and technical skills to drive forward the installation and operation of the commercial biohydrogen technology. This is very important for the sustainability development because for many communities their socioeconomic opportunities presented by the technology makes a difference in their lives. At current conditions, the biohydrogen technology in the urban settings is not sustainable, but it showing social benefits to the local communities. The implementation of the biohydrogen technology in urban setting will promote technological learning and development at this stage. The technology learning stage provides an opportunity for identification of the optimization factors that will improve the yields and economic performance of the technology. Furthermore, the inventory data can be achieved to further improve the research and development purposes. It is important to realize that for policy development, informed decisions must be made based on the available body of knowledge.

8.5. Biohydrogen comparison in vehicle operation for three different settings

Figure 33.8 represents the results for the comparison of the application of biohydrogen application in FC vehicles across the three different chosen settings (i.e. agro-industrial, urban and rural). The agro-industrial setting commands the sustainability performance index value of 0.90, while both the urban and rural settings report the economically unsustainable outcome for the case of the application of biohydrogen in vehicle operations. The application of the biohydrogen produced brewery wastewater in the agro-industrial settings for vehicles operations records the economic performance value of 0.35. The results strongly demonstrate that the economic dimension plays a critical role to determine the viability of the energy infrastructural technology. The economic dimension is very critical and important across the entire production and application of the fuel technology. The results clearly show that the application of biohydrogen technology is unsustainable and should be rejected for implementation for both the urban and rural settings. This is due to the poor economic performance of the application of biohydrogen produced from OFMSW and cattle manure, respectively.

The economic performance is undoubtedly one of the dimension of sustainability that play a crucial role in determining the sustainability of the energy infrastructural development. The introduction of FC vehicles faces serious challenges in relation to economic performance. However, several stakeholders must provide funding and incentives to drive forward the biohydrogen technology for vehicles operation. This can be done through capital investment and funding from the government sector for the purpose of the research and development. The implementation of the infrastructural technology for biohydrogen production is regarded as risky and uncertain at the moment, but it is important to highlight that over time, as the research is improving, the technology will come into maturation stage. The biohydrogen implementation technology will provide opportunities for new business opportunities in the settings for both skilled and unskilled community members.

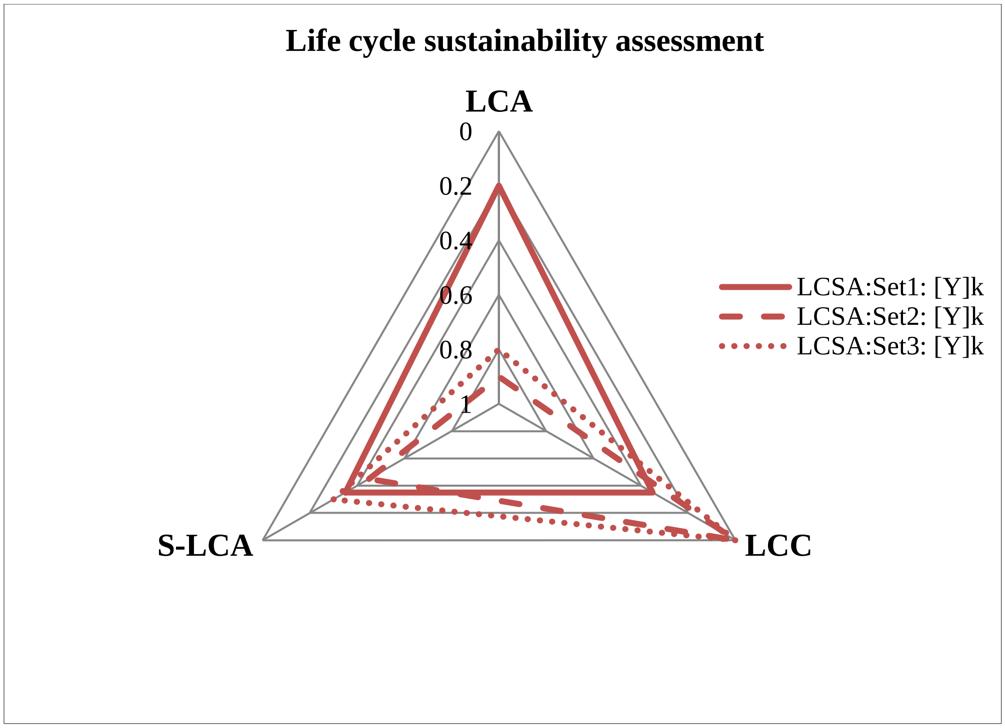

Figure 33.8: Comparison of sustainability performance of the application of biohydrogen as a fuel for vehicles in three different settings.

The three dimension of sustainability play a critical role in influencing the sustainability performance of the production and application of the gaseous biofuels. As in the case for the application of the biohydrogen use as vehicle fuel, the environmental performance differs among the three study settings that are considered in this study. The results indicate that the urban setting improves the environmental performance with the impact value of 0.90, followed by rural setting which records the value of 0.80 and finally the agro-industrial setting records the least environmental performance value estimated at 0.20. It is important to emphasize that all the three dimension of sustainability (i.e. environment, economic and social) have the same equal potential to influence the outcome of the sustainability performance of the biohydrogen technology.

It is imperative to note that the urban setting commands the most sustainable social impact which stands at 0.45, when compared with the agro-industrial and rural settings with sustainable social impact estimated at 0.35 and 0.30, respectively. The urban setting has an abundance of the well-educated persons with technical skills to support the infrastructural development for biohydrogen technology. The results of this study demonstrate that the application of the biohydrogen in the vehicle operation will greatly result in improved social performance in this setting. This is important because the urban setting consists of communities that can support the development of innovative solutions, such as intake of the FC vehicles. To improve the viability of bioenergy programs, it would be desirable to implement the biohydrogen technology in the urban setting for the purpose of technological learning stage. The installation of biohydrogen infrastructural development for the purpose of technology learning stage will assist the LCA practitioners with access to life cycle inventory databases, which help to overcome the significant data shortcomings that exist. The technological learning will be very useful in feedstock production and studying all the conversion production efficiencies of the biohydrogen technology. This might subsequently improve the costs that are associated with feedstock collection and associated production costs of the biohydrogen technology.

The urban setting is the "hotspots" for the installation of advanced technology in order to achieve sustainable production and consumption of the future energy carrier. Clearly, the energy demand is expected to increase due to the urbanization, which is expected to increase in major cities around the world in the coming decades. The installation of the innovative energy infrastructural systems in urban systems is meant to benefit the local communities rather than the agro-industrial setting, which reflects the commercial utilization of the gaseous biofuels. The communities in urban settings can afford implementation of the innovative technologies due to the economic potential of the geographical location. The urban settings present the economic opportunities in the immobilization or generation of the biofuel feedstocks. It opens economic opportunities for ordinary people to supply feedstock for renewable energy generation technologies. This will improve the transport of the infrastructure of feedstock and create economic development for the local people. To build up large volumes of feedstocks and set up decent infrastructure in developing regions would require time to implement. It is important to realize that the implementation of the energy infrastructural development for energy generation is complex and differs from one setting to the other. The urban setting has the opportunity to build the skill capacity for the operation of the energy infrastructural development.

The results of this study indicate that the geographical setting plays a crucial to influence the sustainability performance of the energy generation technologies. The different geographical settings have a different economic outlook which influences the affordability of the production and application of gaseous biofuels. The different geographical locations have access to different services, infrastructural development, etc. If the local economic situation is attractive, the geographical settings in the agro-industrial settings is attractive due to better economics and access to technical skills to drive the services for the biohydrogen production process. The agro-industrial setting reflects the insights of the commercial utilization of the biohydrogen as the energy carrier for the electricity generation. However, the urban setting is showing better social benefits when compared to the agro-industrial settings. This shows the insights on the social benefit for biohydrogen technology implementation for the local communities.

The results of this study indicate that the application of biohydrogen technology in FC vehicles is unsustainable for study scenarios presented in urban and rural setting, while is showing opportunities for implementation in the agro-industrial settings. This is mainly due to the economic aspects of the fuels. It is important to recognize that the choice of feedstock utilization in the different settings plays a crucial role to determine the overall sustainability performance. At the moment the utilization of the brewery wastewater for the production of biohydrogen for application in the fuel cell vehicles should be pursued in the agro-industrial settings. However, the application of the biohydrogen produced from OFMSW and cattle manure is not sustainable. This is due to the fact that the thermophilic fermentation process results to low productivities and low production yields. The low productivities affect the energy fuel outputs, thus influencing the distance travelled by the utilization of the particular fuel type. The results of this study show that among the three feedstocks, the brewery wastewater provide the sustainable outcome when compared with OFMSW and cattle manure, respectively.

8.6. The drafted stakeholder analysis for the sustainability assessment of energy systems

Sustainability considers the measurements of the three dimensions in and holistically approaches, namely: environment, economic and the social aspects. As mentioned before, this study provides the methodological approach for the comparison of the sustainability performance of gaseous biofuels infrastructural development in three geographical settings. The comparison of the study scenarios is based on the application of the energy fuels in the electricity generation systems and also in vehicles operations. It is important to highlight that societies meet their production and consumption patterns through the implementation of various technologies, and these technologies assist the societies to achieve development, which may, however, be sustainable or not. It is important to consider the sustainability of the gaseous biofuels and take into account all the stakeholders that play a role in the implementation of energy infrastructural development. There are several key stakeholders that should be considered for the energy infrastructural development, including investors, contractors, suppliers, local people, competitors, consumers, government, etc.

This study provides the stakeholder analysis whereby different stakeholders such as government, companies primarily in the energy sector, end users (domestic uses, humans etc.), and non-governmental organizations (NGOs), can collaborate and their associated impacts be clearly understood in the three dimension of sustainability. The stakeholder analysis provides the approach for mapping relevant impacts indicators for energy infrastructural systems across the three dimension of sustainability. The stakeholder analysis has a role to play in the policy development by creating awareness between government, energy users and energy companies. Therefore, social driven sets of indicators were successfully developed to social life cycle assessment (S-LCA) activities. The developed stakeholder analysis was explicitly discussed and the framework for their operations and activities was drafted, as presented in Figure 34.8.

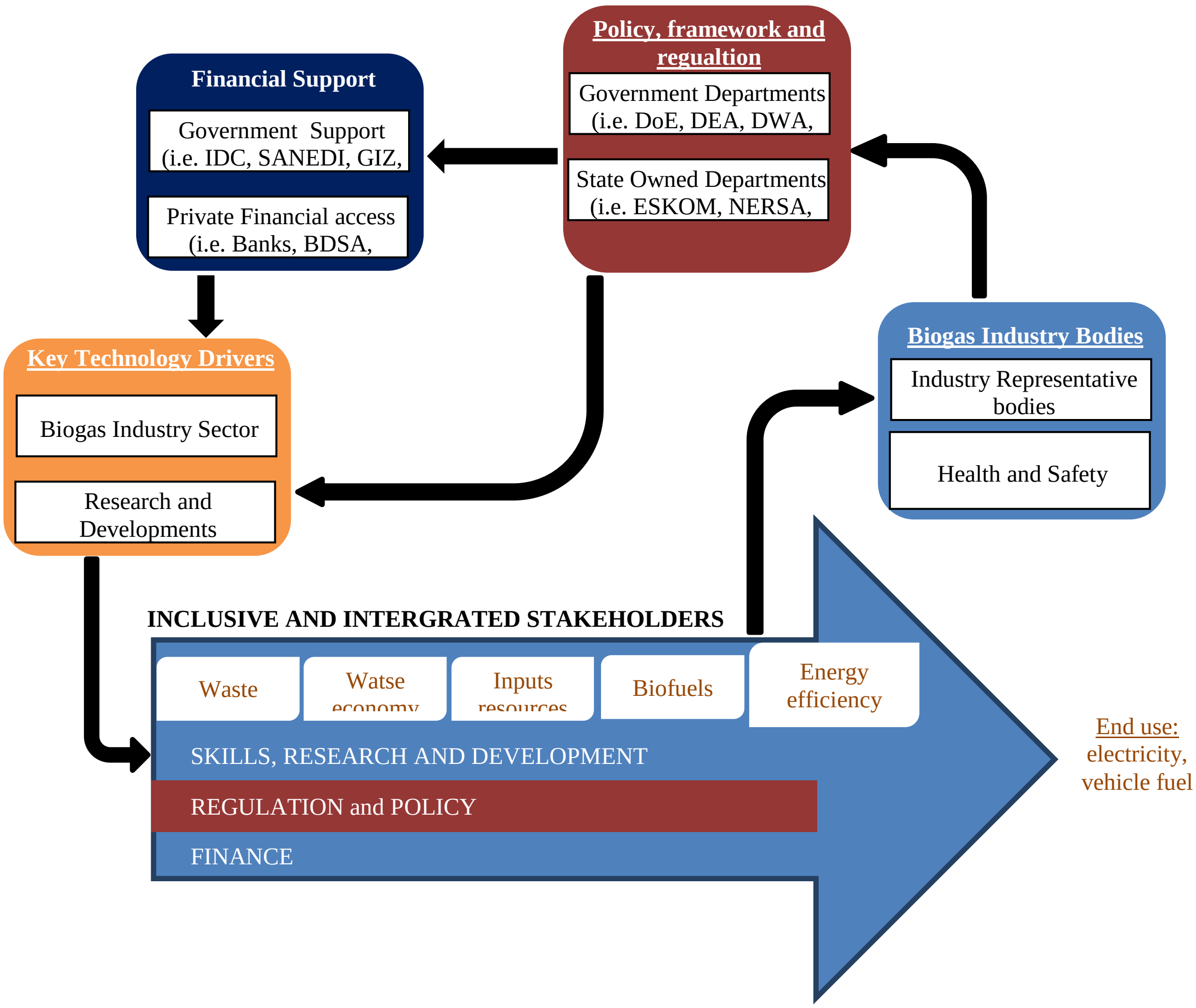

Figure 34.8: One of the key novel of this research showing the developed and drafted sustainability framework (a stakeholder analysis), presenting all the framework of the gaseous production from organic wastes.

Social Life Cycle would be easily accessed and sustainable when human activities, lifestyles and habits are re-oriented to think less of biomethane and be more innovative with constructive minds on biohydrogen production and application. Therefore, the life cycle tools such as life cycle sustainability assessment (LCSA) plays an important role to establish a decision support tool for sustainability assessment of energy infrastructural systems. The choice of implementation of the particular technology should be based on the use of instruments and tools that allow rational selection of alternatives with high sustainability performance. The future of energy use would be sustainable with minimum environmental impacts, economic feasibilities and social considerations when alternatives measures in terms of instruments and tools can be substantially improved. The key element of social consideration in the Life Cycle Assessment is the human factor. Benoît (2009) stated that social indicators that measure social impact in the Life Cycle Sustainability Management (LCSM) is primarily based on people’s well-being in the entire programme cycle. Such factors answer the questions of how, where, who and to whom in the Life Cycle Management applies. The objective of the Social Life Cycle is to set policy, agenda and institutional framework that are relevant to the sustainability of the overall Life Cycle Management. Such policy will be transparently, consistently and accurately pursued in the interest of the environment. Clearly, great developments towards S-LCA have been proposed and discussed by these studies. This study provides a very innovative framework for stakeholder analysis, which includes the entire sustainability performance approach based on the life cycle sustainability assessment (LCSA) approach.

The sustainability of LCSM strategically depends on the synoptic management of the triple bottom line and explains how environment, social and economic assessment can be translated into real life decision processes. Real life decision processes of the respective socio-economic and environmental assessment will be elusive without the “Stakeholder Analysis Phase.” It becomes achievable when the defining roles of the different participating stakeholders along the entire life cycle of the assessment are strictly outlined and transparently pursued. Throughout the life cycle, different stakeholders’ interest must be identified and a sustainable framework must be developed before efficient resource control can be harnessed and sustainable for future generation. Furthermore, different exists in the particular geographical location and all relevant impact indicators must be identified and properly managed collaboratively in order to have smooth successful integration of sustainability initiatives. Therefore, this study has made a breakthrough in the development of the LCSA framework.

The approach towards sustainability development nowadays takes place at the end-game application products. Therefore, there is a great need to develop an appropriate strategy to evaluate the performance products across their entire life cycle stages. In this study, two energetic carriers, namely, biomethane and biohydrogen, are produced via the biological processes, anaerobic digestion and thermophilic fermentation. The end application of these two energetic carriers can be either as fuels for electricity generation or as fuel for vehicles. Biohydrogen is currently promoted as the valuable energy carrier of the future, and in terms of sustainability profiling this fuel is a leader in terms of its value as a product, its uniqueness, its contribution to society, and also its competitiveness in comparison to other available similar products in the market. On the other hand, biomethane is a matured technology when compared to biohydrogen; therefore, this study took an opportunity to compare the sustainability of the new technology using the infrastructural development of the old technology.

9. CHAPTER 9: CONCLUSIONS AND RECOMMENDATIONS

This chapter provides the conclusions and recommendations developed in this study.

9.1. Conclusions

In chapter 3, five research questions were developed for the thesis. Each is discussed and answered below:

- ***Which energetic yields can be achieved by biohydrogen relative to biomethane for typical feedstocks?***

Generally, studies that report on the comparative sustainability performance of gaseous biofuels such as biomethane and biohydrogen for their cradle-to-grave analysis are limited in literature. This study deals with the comparison of life cycle sustainability assessment (LCSA) of two different technologies, biohydrogen production by thermophilic dark fermentation process (TDFP) and biomethane production by anaerobic dark fermentation process (ADFP). It considers the utilization of three different feedstocks, viz. agro-industrial (exemplified by brewery wastewater), urban (OFMSW), and rural organic wastes (cattle manure). Published works show that the anaerobic dark fermentation process (ADFP) achieves significantly higher energetic yield when compared to the thermophilic dark fermentation process (TDFP), for the three substrates respectively. It is estimated that the TDFP needs to improve by 62% for them to be comparable to those of biomethane efficiencies. This difference in energetic yields significantly impacts on all further sustainability assessment, as the energy recovered is further used in the application stages for both electricity generation and as fuels for the vehicle operations. The application of biomethane for both cases of electricity generation and vehicles operation is showing higher sustainability performance in the urban and rural settings, when compared to those of the biohydrogen study scenarios. For the case of the application of biohydrogen in the electricity generation systems commands the highest sustainability performance in the agro-industrial settings when compared to those of biomethane technology. Thus, the application of the biohydrogen technology offers sustainable performance in the agro-industrial settings, but results to unsustainable performance in the urban and rural settings.

The application of biohydrogen in fuel cell systems for electricity generation offers higher energy conversion efficiencies, by up to 80%, in the application stages. For the case of vehicles operation, the biohydrogen conversion efficiencies in fuel cell vehicles achieves the conversion efficiencies of 60%. While the biomethane application in compressed natural gas vehicles are about 40% efficient, while in electricity combine heat and power for electricity generation still remains lower up to 35%. Thus, the biohydrogen technology offers higher energy conversion efficiencies for both cases in the application for electricity generation and also as fuel for the vehicles. The anaerobic digestion process offers higher energy efficiencies during biomethane production stages, but results to lower energy conversion efficiencies during the application of the fuel. While the biohydrogen technology results to lower energy efficiencies about 27% during the thermophilic dark fermentation process (TDFP).

- ***What are the comparative energy and environmental impacts of biomethane and biohydrogen?***

The thermophilic dark fermentation process (TDFP) is associated with lower production yields when compared to the anaerobic dark fermentation process (ADFP). This is despite the fact that the biohydrogen technology requires high chemical and energy inputs during the production of biohydrogen in the TDFP. The technological barrier in the production of biohydrogen remains a concern, but also the socio-technical systems into which the technology would be inserted. However, biohydrogen technology offers some exciting environmental benefits in the end-application for electricity generation and also as fuel for the vehicles. Therefore, there is a need to improve the production efficiencies of the biohydrogen technology during the thermophilic dark fermentation process.

The use of biomethane in the combined heat and power (CHP systems) for electricity generation offers higher environmental performance for both agro-industrial and urban settings when compared to the application of fuel in compressed natural gas (CNG vehicles). However, the biomethane application in compressed natural gas vehicles offers similar comparable environmental performance with those of electricity generation in the rural settings. The biohydrogen technology, on the other hand, offers higher environmental performance in the fuel cell (FC vehicles) than for electricity generation in the fuel cell (FC systems) for both urban and rural study settings. While the biohydrogen technology is showing better environmental performance in the agro-industrial settings when compared with the other settings. Clearly, the biomethane technology offers environmental improvements in the electricity generation systems while the biohydrogen offers great environmental intervention in the vehicles operations. However, at the moment the biohydrogen technology still offers worse environmental performance when compared to the biomethane technology. This is due to the fact that the biohydrogen technology results to worsened environmental performance during the generation stage of the biohydrogen rather than the application stages. In fact, the biohydrogen technology offers lower environmental emissions in the end-use of the biohydrogen in electricity generation systems and also in vehicles operations.

- ***How can biogas be used best to maximize resource efficiency and to enable sustainable development in different African settings (industrial, urban, and rural)?***

Often societies meet their production and consumption patterns through the implementation of various technologies, and these technologies must enable societies to achieve sustainable development, resulting in durably improved living conditions, achieved through economic development. The installation of energy technologies (incl. those for gaseous biofuels) in different geographical locations requires sustainability assessment. This has been done in this thesis, not only for the production of the energy fuels, but also considering their application, especially in electricity generation and also in vehicles operations. Clearly, at the moment the application of biomethane for in electricity generation or for vehicles shows a better sustainability performance than the biohydrogen technology in the urban and rural settings. However, the biohydrogen technology is useful and suitable for installation in the agro-industrial settings for both electricity generation and vehicles operation. It is important to point out that the biohydrogen technology requires sophisticated infrastructure which is potentially available in the agro-industrial settings.

The agro-industrial settings provide an opportunity for technology learning and further development of the biohydrogen technology for vehicles operations. It has been observed that in order to achieve high energy production efficiencies, the digester requires skilled technicians to improve the operational conditions. Furthermore, the agro-industrial settings may well provide access to infrastructure that is needed to for the installation and operation of the biohydrogen technology.

- ***What are the sustainability benefits and costs of introducing biohydrogen?***

The core function of technology is to bring about a service, in an economically sensible practice and in a sustainable manner. At current energy yields, biomethane is preferred over biohydrogen for energy from waste installations. Biohydrogen offers potential opportunities in the agro-industrial settings, but not in the urban and rural settings. This follows primarily from the much higher biohydrogen yields reported for brewery wastewaters than for the other exemplary substrates (both OFMSW and cattle manure).

The poor sustainability performance of the biohydrogen technology when compared to biomethane application can be attributed to various factors such as lower conversion efficiencies, higher energy inputs and higher chemical inputs that are required for the dark fermentation process. Again, the energetic value for both production and conversion efficiencies plays a crucial to determine the economic performance of the technology. It is important to realise that the higher energetic conversion efficiency of the biohydrogen technology improves the economic performance. Furthermore, the installation and operation of the biohydrogen technology is largely influenced by the economic status of the geographical region where the technology is inserted. The geographical settings with high economic potential consist necessary technical skills which is required for the operation and maintenance of the technology. The implementation of the biohydrogen technology is suitable for installation in the agro-industrial settings whereby there is access to relevant stakeholders to support the research and development of the technology.

The agro-industrial settings often have a demand for electricity generation, industrial heat (provided by steam) and vehicles operation fuels (i.e. biomethane and biohydrogen). Biomethane, now produced increasingly from agro-industrial wastes, can meet all of these. If the biohydrogen technology could achieve somewhat higher yields, it would have potential to introduce fuel cells to this industry, to generate more electricity (but less heat) or propel vehicles further. Switching from biomethane to biohydrogen technology would be a multi-faceted decision. Amongst other criteria, its need for highly skilled technicians for the operation of the biohydrogen technology needs to be considered.

- ***How can Social Life Cycle Assessment (S-LCA) be used within the context of Life Cycle Sustainability Assessment (LCSA) in energy technology assessments?***

The findings of this study are to some extent influenced by geographical settings of which the technology is inserted. The proposed framework of life cycle sustainability assessment should focus on the three (3) separate assessments, taking into account the three dimension of sustainability, i.e. social, environmental, and economical. This ensures that all dimension of sustainability along the life cycle-based modelling structure are taken into account to avoid issues in problem shifting. For this reason, definitely the holistic way of the three dimension of sustainability is progressive, but further broad practical correlation needs to be established between technology choice and potential impacts along the stakeholder groups. This thesis has presented a broad practical approach towards mapping of potential social impacts using the stakeholder analysis to consider the complete life cycle of products. After all, the social aspect considers the well-being of stakeholders of the introduction of new energy technology.

This study offers important information for decision makers regarding the sustainability performance of energy infrastructural development, specifically for cases of biohydrogen vs. biomethane energy generation technology. The results of this study provide clarity in terms of which energy generation technology and application should be pursued at the three selected geographical settings. It highlights the energetic benefits and sustainability performance that can be achieved from the three selected waste streams. In terms of sustainability performance, this study has successfully demonstrated the trade-offs between the three dimension of sustainability and their role in influencing the sustainability performance of renewable energy technologies. Furthermore, this study provided a methodological approach for real case studies for life cycle sustainability assessment of energy infrastructural development in different African context.

The drafted sustainability framework (a stakeholder analysis) presents all the stakeholders to be considered for the assessment of sustainability performance of gaseous biofuels from different organic waste-based residues. The framework is of practical value as it can be used as a guideline by project developers who wish to improve collaboration with stakeholders along the entire production and application of gaseous biofuels. This fills a gap in the academic literature where there is only limited research on sustainability stakeholder management for new energy infrastructural development.

In this study, the investigation of social impact of the biofuels technologies was informed by considerations of the geographical location where the technologies could be implemented. It was shown that the social impact indicators differed in the different geographical locations, and thus influence the sustainability performance of the gaseous biofuel technologies. Importantly, the S-LCA was shown to offer a framework to improve collaboration with stakeholders along the entire energy production and use chain; and also could help develop 'technology learning' strategy. Considerations of infrastructural development should be inclusive of techno-economic factors, social infrastructure and the region's readiness (policy development, power and utility agreement, licensing and regulatory framework, etc.).

9.2. Recommendations

Based on the conclusions reached in answering the research questions posed in this thesis, the following five recommendations are made:

- ***Turn waste into biomethane for now in all settings, and use it for electricity or to propel vehicles***

The anaerobic dark fermentation process (ADFP) offers viable biomethane yields during the energy generation process, while, the thermophilic dark fermentation process (TDFP) still faces major challenges related to the production efficiencies for them to be comparable to those of the biomethane technology. At the moment more information and knowledge development should be made available for installation and operation of the biomethane technology for application in electricity generation systems or as fuel for vehicles. It remains possible that biomethane infrastructural development could serve as a precursor for the infrastructural development for the hydrogen economy in South Africa.

- ***More R&D to improve biohydrogen yield, esp. from agro-processing wastes***

At the moment the thermophilic dark fermentation process (TDFP) for biohydrogen generation faces several challenges related to low hydrogen yields, high energy inputs, and high chemical inputs. On the other hand, the end-use of the biohydrogen in the electricity generation systems and vehicles operation is associated with high energy conversion efficiencies. Therefore, research and development should be encouraged to improve the production of biohydrogen, focusing on collection, pre-treatment and bioconversion processes for biohydrogen production. Definitely, the agro-industrial sector has the greater opportunity to advance and add value to the implementation of the biohydrogen technology.

- ***Understand fuel and energy demand in different developmental settings, now and in the future***

The outcome of this study demonstrates that the insertion of biohydrogen technology depends largely on the infrastructural development that is available in the region. The infrastructural development needs to be clearly defined and established in order to support the implementation of the sustainable energy fuel production. It is important to establish the status of infrastructural development in terms of access to services, human capacity (for example well-trained technicians), and region readiness for the construction and operation of the biohydrogen technology. Furthermore, the focus should not only involve the technology assessment in order to ensure cities implement sustainable energy generation technologies, but also should investigate factors that drives fuel/energy demand in different geographical locations.

- ***Start building a skills base for generation and utilisation of hydrogen in the agro-industrial sector***

The installation of the biohydrogen technology in the agro-industrial settings is not a trivial undertaking but requires fairly extensive technical expertise and knowledge. The operation of the thermophilic dark fermentation process requires highly skilled technicians in order to achieve increased biohydrogen productivities. It is recommended that skills development programmes are initiated to build human capacity for the hydrogen economy in order to drive forward the innovation of new energy infrastructural development.

- ***Social-LCA should be included in energy infrastructure planning***

There is a need to develop a proper energy planning process for African waste-to-energy projects (incl. in agriculture, for municipal solid waste, and for commercial and industrial wastes) and project future energy requirements. This has to be done in a sustainable way by launching a multidisciplinary approach to provide clear technical studies that link energy planning to the sustainable development goals (SDGs). The life cycle sustainability assessment (LCSA) is a very useful methodological approach for selecting the impact indicators across the three dimension of sustainability. In particular, there is a need for studies that include appropriate measures of social impact indicators for energy infrastructure planning within the context of sustainability. It is recommended that there should be transparency and early community engagement during technology development stages to enhance technology acceptance.

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11. APPENDICES

Appendix 1: Impact categories of the of the life cycle impact assessment when applying the ReCiPe methodology.

Impact categories	**Description**	**Characterisation factor**
Ozone depletion	Destruction of the stratospheric ozone layer by anthropogenic emissions of ozone depleting substances	Yr./kg CFC-11 (Chlorofluorocarbons) equivalents
Human toxicity and ecotoxicity	Human toxicity and ecotoxicity accounts for the environmental Persistence (fate) and accumulation in the human food chain (exposure), and toxicity (effect) of a chemical.	Yr/kg 1,4-dichlorobenzeen (14DCB)
Radiation	Ionizing radiation accounts for the level of exposure of radiation material	Yr/kg Uranium 235
Photochemical oxidant formation	Here marginal change in the 24h-average European concentration of ozone (dCO_3 in $kg \cdot m^{-3}$) due to a marginal change in emission of substance x (dMx in kg·year–1) is measured	Yr/kg NMVOC (Non-methane volatile organic compounds)
Climate Change	This impact measures the global warming potential	Yr/kg CO_2 (Carbon dioxide)
Agricultural and urban land occupation	The amount of either agricultural or urban land occupied for a certain time	m^2*year
Natural land transformation	Natural land transformed and occupied for a certain time	m^2*year
Marine Eutrophication	Accounts for the environmental persistence (fate) of the emission of N containing nutrients	Yr/kg N
Fresh water eutrophication	accounts for the environmental persistence (fate) of the emission of N containing nutrients	Yr/kg N
Fossil fuel depletion	It is the amount of extracted fossil fuel extracted, based on the upper heating value	MJ (Megajoule)
Minerals depletion	Minerals depletion is the decrease in grade	kg Iron (Fe) equivalent
Fresh Water Depletion	Depletion is defined as amount of fresh water consumption	m^3
End-point		
Human Health	This is expressed as the number of year life lost and the number of years lived disabled	Disability Adjusted Life Years (DALYs)
Ecosystems	The loss of species over a certain area, during a certain time	Years
Resources Surplus cost	Expressed as the surplus costs over an infinitive timeframe, considering a 3% inflation	

Appendix 2: Categories and subcategories for elementary flows in ecoinvent data.

Category	Subcategory	Definition	Assign general to
air	Low population density	Emission in areas without settlements or protected areas in the direct surrounding	Resource extraction, forestry, agriculture, hydro energy, wind power, coal and nuclear power plants, municipal landfills, wastewater treatment. Long-distance transports, shipping
	Low population density, long-term	Emissions which take place in the future, 100 years after the start of the process	Emissions from Uranium mill tailings
	Lower stratosphere + upper troposphere	Emission from air planes	Air transport cruises
	High population density	Emissions near settlements or protected areas which affect directly people or animals due to the local situation. Most important for particles.	Industry, oil and gas power plants, manufacturing, households, municipal waste incineration, local traffic, construction processes.
	Unspecified		Only used if no specific information available
Resource	In air	Resource in air, for example Argon, carbon dioxide	Used for carbon uptake in biomass and gases produced by air separation
	biotic	Biogenic Resource, for example wood	
	In ground	Resource in soil for example ores, but also for landfill volume	
	land	Land occupation and transformation	
	In water	Resource in water, for example magnesium, water	
Soil	agriculture	Emission to soil used for the production of agriculture products	Agriculture
	Forestry	Emission to soil used for plant production (forest, renewable raw materials) which do not enter the human food chain	Forestry
	Industrial	Emission to soil used for industry, manufacturing, waste management and infrastructure.	Industry, land farming of wastes, built-up land.
	Unspecified		Only used if no specific information available
Water	ground	Ground water which will get in contact with the biosphere after some time.	
	Ground-, long-term	Emissions which takes place in the future, 100 years after the start of the process	Long-term emissions from landfills
	Lake	Lakes with sweet water	
	Ocean	Ocean, sea and salty lakes	Offshore works, overseas ship transports.
	river	Rivers	Discharge of effluents from wastewater treatments facilities
	River, long-term	Emissions which take place in the future, 100 years after the start of the process	Long-term emissions, subcategory not used in ecoinvent database
	fossil	Salty ground water that does not get into contact with the biosphere	Re-injection of formation water from oil- and gas extraction, subcategory not used in ecoinvent database
	Unspecified		Only used if no specific information available

Appendix 3: airborne pollutants.

Name	Formula	Remarks
Particulate, < 2.5 um	PM2.5	Particulates with a diameter of less than 2.5 µm
Particulates, > um and <10 um	PM10-PM2.5	Particulates with a diameter of more than 2.5 µm and less than 10 µm
Particulates, > 10um	TPM-PM10	Particulates with a diameter of more than 10 µm
PM2.5 particulate matter with a diameter of less than 2.5 µm; PM10 particulate matter with a diameter of less than 10 µm; TPM total particulate matter		

Appendix 4: LCA and LCI software tools, vendors, and websites.

Tool	Vendor	URL
GREET	US DOE's Office of transport	www.transportation.anl.gov/software/GREET/index.html
SimaPro 7.1	PRe Consultant	www.pre.nl/simapro.html
DOE = Department of Energy; GREET = Greenhouse gases, regulated emissions, and energy use in transportation, US = United state		

Appendix 5: Showing the research development for biogas projects that are carried at various South African Universities and research other research institutions

Project location	Process	Feedstock	Product	Contact
Cape Peninsula University of technology	Anaerobic digestion	Food waste, plant waste, municipal solid waste, industrial waste such as winery waste	Biogas/methane	Dr Vincent Okudoh
Durban university of technology	Dark fermentation	Crop residues – sugarcane bagasse	Biohydrogen	Prof. Faizal Bux
Mangosuthu University of Technology	Anaerobic digestion, dark fermentation	Wastewater, industrial wastes, animal waste, plant wastes and by-products	Biohydrogen, biogas	Prof. Akash Anandraj
Vaal University of Technology	Integrated anaerobic digestion and photodegradation	Wastewater, industrial waste. Food waste, sewage sludge, Abattoir waste	Biogas	Prof. Ochieng Aoyi
North-West University	Anaerobic digestion	Sewage sludge, Faecal sludge	Biogas	Prof. Carlos Bezuidenhout
Rhodes University	Microbial fuel cells	Wastewater, brewery wastewater		Prof. Janice Limson
University of Cape Town	Anaerobic dark fermentation, Dark fermentation,	Domestic wastewater, industrial wastewater, food waste, sewage sludge, plant wastes and by-products, Algal residue, crop residues, process residues	Biogas and biohydrogen	Prof Sue Harrison
University of Cape Town	Anaerobic digestion	Municipal solid wastes, municipal wastewater, livestock manure	Biogas	Dr Amos Madhlopa

University of Cape Town	Anaerobic digestion	Municipal solid waste, wastewater, industrial waste, food waste	Biogas	Dr Bothwell Batidzirai
University of Cape Town	Anaerobic digestion	Wastewater industrial waste, food waste, animal waste	Biogas, biohydrogen	Prof. Harro von Blottnitz
University of Fort Hare	Anaerobic digestion	Animal waste	Biogas	Dr Sampson Mamphweli
Prof. Edison Muzenda	Anaerobic digestion	Municipal solid waste, wastewater, industrial waste, food waste, crop residues	Biogas	Prof. Edison Muzenda
University of Johannesburg	Anaerobic digestion	Municipal solid waste, wastewater, industrial waste, food waste, animal waste	Biogas, biohydrogen	Dr Akinwale Aboyade
University of KwaZulu Natal	Anaerobic digestion	Food waste and farm waste	Biogas	Prof. Cristina Trois
University of KwaZulu- Natal	Anaerobic digestion	Organic biomass	Biogas	Prof. Stefan Schmidt
University of KwaZulu Natal	Anaerobic digestion	Animal waste, food waste, wastewater	Biogas	Dr Terry Everson
University of Pretoria	Anaerobic digestion	Municipal wastewater, wastewater, industrial waste, food waste	Biogas	Prof. Diane Hildebrandt
University of South Africa	Anaerobic digestion	Dairy manure, kitchen waste	Biogas	Dr Martin Myer
University of Venda	Anaerobic digestion	Municipal solid waste, wastewater, industrial waste, food waste, animal waste, etc.	Biogas	Dr David Tinarwo
University of Witwatersrand	Dark fermentation	Wastewater organic material	Biohydrogen	Prof. Vincent Gray
University of Witwatersrand	Anaerobic digestion	Municipal solid waste, wastewater, industrial waste	Biogas, biohydrogen	Prof. Sunny Lyke
Agricultural council	Anaerobic digestion	Cattle manure	Biogas	Mr Petrus Britz
Council for industrial and scientific research	Anaerobic digestion	Wastewater, sewage sludge, animal waste	Biogas	Ms Dabbie Jooste

Appendix 6: Showing industrial developments of some of the major biogas project that are implemented at various locations across the country

No	Project location	Status	Technology	Waste type	Energy use	Developer
1	Springs-Johannesburg		Combined heat and power	Abattoir waste	Electricity	Biogas SA
2	North West Province		Rural biogas	General rural waste	Domestic use	Biogas SA
3	Johannesburg		Floating dome	Food waste	Electricity	Biogas SA
4	Gauteng	Built	Anaerobic digestion	WWTW	Electricity	Joburg Water
5	Gauteng	Built	Anaerobic digestion	WWTW	Electricity	Joburg Water
6	Cape Town		Anaerobic digestion	Assorted MSW	Upgraded biogas	Marcelle Steinberg
7	City of Cape Town-Phillippi	Existing – 2012	Anaerobic digestion	MSW organics + sewage		
8	Cape Winelands	Existing – 2014	Anaerobic digestion	MMSW + sewage		
9	City of Cape Town	Existing– 2007	Anaerobic digestion	Volatile animal waste + sewage		
10	Overberg – Stanford	Existing – 2006	Anaerobic digestion	MSW organics + sewage		
11	West Coast – Riebeeck Valley	Existing – 2007	Anaerobic digestion	MSW + sewage		
12	West Coast – Groot Winterhoek	Existing – 2005	Anaerobic digestion	MSW+sewage		
13	Cape Winelands – Vrolikheid	Planned – 2015	Anaerobic digestion	MSW + sewage		
14	Cape Winelands – Stellenbosch	Planned – 2014	Anaerobic digestion	Sewage		
26	Overberg – Buffeljachts	Planned – 2014	Anaerobic digestion	Food industry waste		
27	West Coast – Darling	Planned – no approval	Anaerobic digestion	Volatile animal waste		
28	Cape Winelands–- Paarl	Planned – no approval	Anaerobic digestion	Volatile animal waste		
29	Cape Winelands – Bonnievale	Planned – 2015	Anaerobic digestion	Volatile waste		
31	Overberg – Grabouw	Planned – 2015	Anaerobic digestion	MSW - commercial		
32	Cape Winelands – Paarl	Speculation	Anaerobic digestion	Volatile animal waste		
33	West Coast – Voorpaardeberg	Planned – 2017	Anaerobic digestion	Volatile animal waste		
34	Cape Winelands	Planned – 2015	Anaerobic digestion	Volatile animal waste + organic waste + sewage		
35	West Coast – Malmesbury	Planned – 2015	Anaerobic digestion	Volatile animal waste		
36	City of Cape Town	Planned – 2017	Anaerobic digestion	Organics + sewage		
37	City of Cape Town	Existing	Anaerobic digestion	Organics and sewage solids		
MSW = municipal solid waste; SA = South Africa; WWTW = wastewater treatment works						

Appendix 7: The consent form

Dear Participant,

My name is Phumlani Masilela, a PhD student in the Department of Chemical Engineering of the University of Cape Town. I am undertaking a research study to investigate the full economic value, social and environmental benefits of the biogas digesters installed in Giyani located in the province of Limpopo. The key focus of the research is to identify key barriers/challenges of currently operational biogas digester, and investigate whether the uptake of advanced technologies (such as biohydrogen technology) can be socio-technically supported in these settings. You are invited to participate by answering the attached questionnaire that would take about 20-30 minutes of your time. There are no costs associated with this study (for example transport, payment/reimbursement, etc.); you will be visited at a location suitable to you.

The collective findings of this study will be captured in a thesis/report that will be presented to the University of Cape Town for academic purposes. The findings will be also published in an academic journal or presented at a conference if the information is deemed of academic value. The benefit of participating in this study is that more knowledge will be generated to further improve knowledge regarding installations and operational of the biogas digester technologies.

There is no any harm associated with this study and the choice to participate is yours alone. If you choose not to participate, there will be no consequences. If you wish to participate and choose to withdraw at any time, you will be free to do so without negative consequence. Only your own opinion is important. However, I would be grateful if you would assist me by allowing me to interview you. Please be assured that information provided would be treated confidentially and anonymously in this study.

Thank you for your consideration and participation.
Regards,
Phumlani Masilela

Appendix 8: The field questionnaire for the application during interviews.

Inputs obtained by interview:	
Type of the biodigester	
Village/Location of the digester	
Name of owner	
Operator interviewed	
Tel. number	
Inputs obtain by interview:	
What type of the digester and size (m^3)? Why?	
What is the technical competency, of the biodigester operator? In terms of training and qualification etc.	
What difficulties are encountered during digester operation?	
How long does it take place to repair the digester? Is the reasonable to good access to supply and maintenance of plant and equipment?	
Where/How do you get untreated cattle manure (kg/day)?	
What type of the feedstock is used for the bioprocess in the digester?	
Does the feedstock require pre-treatment stage, or other processing?	
How regular are the feedings and what is the quantity of the cattle manure per feeding (kg/day)?	
List all inputs that are used during biogas production, water, chemicals, etc.	
Use of the biogas:	
Is there any biogas processing before use?	
What is the end-use of the biogas?	
Who are the customers for end production utilization?	
Selling (market) price per quantity sold (R/m^3)	
Use of the gas value (MJ use)	
What is the impact of using the biogas?	
What significance does the biodigester play?	
How does this energy technology change life?	
Impact of biodigester on family fuel needs (households):	
Family compositions (number of males and females)	
Daily biogas stove use (hrs/day/stove)	
Is the biogas enough for 3 meal cooking of the day?	
Daily lamp use (hrs/day/lamp)	
Is the biogas enough for maintaining lights on?	
Person involved and time required (man hours/day)	
The effect of the plant on the household and agricultural practices; has the use of the plant led to work increase or decrease, if so, elaborate	
Estimation of the household saved, and who in the household benefited the most in terms of time savings from the digester	
Educational level of adult(s) in the household	
Family opinions of biodigester	
How is the biodigester performing in changing season, your views?	
What is the technological difficulties and improvement of the biodigester	
What negative or positive impacts experience as a result of biogas utilization	
Project cost (economic issue)	
How much was the overall installation cost of the digester (R/m^3)?	

Provide the breakdown cost for biodigester installation (building materials, appliances, skilled-unskilled labour, participation fee and guarantee fee)	
How much is the biodigester operational cost per month?	
How much is spent on maintaining the digester per month?	
Money spent on electricity before and after installation (R/day)	
What is the value of the biogas, relative to the cost?	
What cost is associated with the collection of the digester feedstock per month?	
Inputs obtained by measurements:	
Substrate type	
For typical feedstock, what energetic yields can be achieved per kg of substrate?	
What are the quantity inputs in the bioprocess per kg of substrate processing?	
What energetic achievements per kg of processed feedstock?	
What are the economic benefits and costs of processing kg of feedstock?	
Operational practice:	
Biogas production per week (for example m^3, tons, etc.)	
What is the biogas production rate?	
What is the biogas production yield?	
What is the biodigester hydraulic retention time?	
What is the operational temperature of the digester?	
Slurry pH	
Slurry temperature (°C)	
What is the content of the cattle manure?	
Residence time (days)	
Biodigester performance:	
Daily operation time (hours)	
Days of gas production (days)	
Gas production (L/min)	
Time to fill gas reservoir (hours)	
Biogas composition (%)	
Biomethane (ml CH_4/kg VS)	
Cooking and lighting:	
What is the cooking energy of the biogas?	
What are the energetic power of the flame, and the efficiency of the gas stove?	

Appendix 9: The inventory data for the S-LCA assessment gathered from various sources: Framework, policy documents, legislation, guidelines and strategy documents.

(A) The inventory data gathered from various sources: Framework

Department of Energy (DOE)	Integrated energy plan and integrated resource plan 2010-2030 (IRP 2010).
	Renewable energy IPP programme.
	The energy efficiency strategy (2005).
Department of Environmental Affairs (DEA)	They have a very strong policy and implementation plan on re-use, recycling and recovery processes.
ESKOM	MTPPP (medium-term power purchase programme
	STPPP (short-term power purchase programme
	WEPS purchase programme (one-year standard offer PPA at the WEPS purchase rate)
	REIPPP (renewable energy IPP poor purchase programme).
	Renewable Energy Feed-in Tariff (REFIT II).
National Energy Regulator of South Africa (NERSA)	NERSA published guidelines for feed-in tariffs.
Industrial Development Corporation (IDC)	IDC in support of greener fuels (biofuels/renewable).
	Baltic Biogas Bus Study 2007-2012
Biogas industry	Exists wheeling agreements (between, Eskom, municipalities, and producers)
	Companies can do business on the green power trading market
	Buying and selling certificates energy from projects
	Power providers can signs PPA with customer (pays same municipal tariff).
	Strong presence of the private sector, when compared to informal sector
	The existing wheeling agreements permit effective trading for renewable energy
	The renewable energy projects are based on the market driven/demand based (willing buyer willing seller).
Academic research institutions	The State of Renewable Energy in SA report (published)
	SA International Renewable Energy Conference (SAIREC)

(B) The inventory data gathered from various sources: Policy documents

Department of Energy (DOE)	White paper on energy policy (1998).
	Energy policy White paper on renewable energy (2003).
	Energy policy and legislative framework (Energy Act No 34 of 2008).
ESKOM	Industry is best supported through strong supportive policy frameworks
National Energy Regulator of South Africa (NERSA)	Renewable energy policy (REFIT)

(C) The inventory data gathered from various sources: Legislation

Department of Energy (DOE)	Gas Act 2001 (Act no. 48 of 2001).
	Clean air/air quality acts.
	Green economy strategy act.
	Energy policy and legislative framework (Energy Act No 34 of 2008).
Department of Environmental Affairs (DEA)	Waste management act.
	Air emissions license.
	Water use licence.
	National Environmental Management Air Quality Act, Act 39 of 2004
	Atmospheric emission licences (AEL),
	National environmental management (waste) act, acts 59 of 2008.
Department of Water Affairs (DWA)	Water services act, 1998 (Act No. 36 of 1998),
	Water usage licences
Department of Labour	Occupational safety and hazards act, 1993 – act No. 85 of 1993
National Energy Regulator of South Africa (NERSA)	Gas Act 2001, (Act No. 48 of 2001).
	Piped-gas Regulations, regulation 9(1) and (2)
	Biogas: storage licence, production activity registration, trading license
Biogas industry sector	Occupational Health and Safety Act (Act 85 of 1993).
	Biogas health issues needs to be addressed

(D) The inventory data gathered from various sources: guidelines and strategy documents

Department of Energy (DOE)	No specific standard for biogas sector.
	No specific policy directed to biogas sector.
	Too much paperwork for green projects.
	Complex administrative processes for green project.
	Poor administrative efforts from lower-ranking officials.
Department of Environmental Affairs (DEA)	There is an effective complaint and reporting approach from the department.
	Close relationship between the department and municipalities.
	Municipalities very active on the ground to respond to complains.
	Concerns of escalation of acquiring the EIA clearance in some projects.
Department of Water Affairs (DWA)	Documents went missing.
	Taking long to approve documents.
ESKOM	There is a need to develop a better framework of purchase agreement between the producers and buyers
	On-grid feed in specification seem to be not clear
	More clarity is needed for Feed-in-tariffs
	Concerns over budget quotes between Eskom's and independent power producers (IPPs).
	Eskom strongly takes measures to protect their financial sustainability
	No capital allocation was accommodated for in the current multi-year pricing regime (MYPD3) for IPPs beyond Bid Window 3
	Eskom has committed to continue with the network integration studies
	Concerns over misunderstanding between Eskom and National Energy Regulator (NERSA).
	Eskom avoids reckless trading
	Complex administrative processes for project development and authorisation, especially at municipal level.
National Energy Regulator of South Africa (NERSA)	The owner of a biogas project is required to register with the National Regulator of South Africa (NERSA).
	The Gas Act 2001 is currently in the process of being amended.
South African Bureau Standards (SABS)	No specific standard for biogas is approved in South Africa.
Banks and finance institutions	Lack of biogas dedicated financing mechanism.
	Provision of loan seem to be difficult
	Security of investment is not guaranteed
	Most funds support commercial projects that are close to commercialization
	Biogas technology has high capital cost
	One of the key challenges of the green renewable projects is the issue of funding
	GIZ is playing a crucial role in the development of biogas industry in South Africa
Biogas industry sector	It is possible to develop the biogas technology and retain the full ownership of the company until full financial closure
	The country does not have the effective biogas energy policy to speak of
	Investors, technology suppliers and project developers require clear policy from government
	There is an issue of fraud and corruption is of concern
	Wheeling agreement, trading cap, wheeling fee-should be kept at 20-year agreement.
	Win-win situation- it is to the municipal benefit to support the purchase by Eskom from generators connected to municipality networks - as Eskom will sell this power back to the municipal at rates lower than if Eskom had delivered the energy at the municipality's point of supply.
	The biogas power generation industry is currently developing at such a slow pace.
	The current electricity pricing levels for biogas do not reflect its most valuable component.
	No biogas industry strategy at the moment
	No biogas installation practice has been passed yet
	Equipment standards are still outstanding
	Market restricted by willing buyers
Academic research institutions	Biogas training and education institutions needs to be developed
	Lack of skilled and registered labour force
	Lack of awareness (biogas process technologies)
	Low levels of biogas research
	Lack of skilled human resources.
	Poor promotion of the biogas technology.

Appendix 10: The weighting system for scoring of economic impacts indicators

Assign scores	Assign factor rating		
Range (%)	**Net present value**	**Internal rate of return**	**Pay back period**
≤ 0.00	0.00	0.00	0.00
0.01-1.50	0.10	0.10	1.00
1.51-2.09	0.13	0.13	0.98
2.10-2.68	0.15	0.15	0.95
2.69-3.27	0.18	0.18	0.93
3.28-3.86	0.20	0.20	0.90
3.87-4.45	0.23	0.23	0.88
4.46-5.04	0.25	0.25	0.85
5.05-5.63	0.28	0.28	0.83
5.64-6.22	0.30	0.30	0.80
6.23-6.81	0.33	0.33	0.78
6.82-7.4	0.35	0.35	0.75
7.41-7.99	0.38	0.38	0.73
8.00-8.58	0.40	0.40	0.70
8.59-9.17	0.43	0.43	0.68
9.18-9.76	0.45	0.45	0.65
9.77-10.35	0.48	0.48	0.63
10.36-10.94	0.50	0.50	0.60
10.95-11.53	0.53	0.53	0.58
11.54-12.12	0.55	0.55	0.55
12.13-12.71	0.58	0.58	0.53
12.72-13.3	0.60	0.60	0.50
13.31-13.89	0.63	0.63	0.48
13.90-14.48	0.65	0.65	0.45
14.49-15.07	0.68	0.68	0.43
15.08-15.66	0.70	0.70	0.40
15.67-16.25	0.73	0.73	0.38
16.26-16.84	0.75	0.75	0.35
16.85-17.43	0.78	0.78	0.33
17.44-18.02	0.80	0.80	0.30
18.03-18.61	0.83	0.83	0.28
18.62-19.2	0.85	0.85	0.25
19.21-19.79	0.88	0.88	0.23
19.80-20.38	0.90	0.90	0.20
20.39-20.97	0.93	0.93	0.18
20.98-21.56	0.95	0.95	0.15
21.57-22.15	0.98	0.98	0.13
22.16-22.74	1.00	1.00	0.10

Appendix 11: The weighting system for scoring of impacts indicators for sustainability performance index performance.

Assign score	Assign factor rating		
Range (%)	**Environmental**	**Economic**	**Social**
≤ 0.00	0.00	0.00	0.00
0.01-1.50	1.00	0.10	0.10
1.51-2.09	0.98	0.13	0.13
2.10-2.68	0.95	0.15	0.15
2.69-3.27	0.93	0.18	0.18
3.28-3.86	0.90	0.20	0.20
3.87-4.45	0.88	0.23	0.23
4.46-5.04	0.85	0.25	0.25
5.05-5.63	0.83	0.28	0.28
5.64-6.22	0.80	0.30	0.30
6.23-6.81	0.78	0.33	0.33
6.82-7.4	0.75	0.35	0.35
7.41-7.99	0.73	0.38	0.38
8.00-8.58	0.70	0.40	0.40
8.59-9.17	0.68	0.43	0.43
9.18-9.76	0.65	0.45	0.45
9.77-10.35	0.63	0.48	0.48
10.36-10.94	0.60	0.50	0.50
10.95-11.53	0.58	0.53	0.53
11.54-12.12	0.55	0.55	0.55
12.13-12.71	0.53	0.58	0.58
12.72-13.3	0.50	0.60	0.60
13.31-13.89	0.48	0.63	0.63
13.90-14.48	0.45	0.65	0.65
14.49-15.07	0.43	0.68	0.68
15.08-15.66	0.40	0.70	0.70
15.67-16.25	0.38	0.73	0.73
16.26-16.84	0.35	0.75	0.75
16.85-17.43	0.33	0.78	0.78
17.44-18.02	0.30	0.80	0.80
18.03-18.61	0.28	0.83	0.83
18.62-19.2	0.25	0.85	0.85
19.21-19.79	0.23	0.88	0.88
19.80-20.38	0.20	0.90	0.90
20.39-20.97	0.18	0.93	0.93
20.98-21.56	0.15	0.95	0.95
21.57-22.15	0.13	0.98	0.98
22.16-22.74	0.10	1.00	1.00

Appendix 12: Results of sensitivity analysis of the life cycle sustainability assessment (LCSA) in percentage

Environmental indicators (5%)		
LCSA:Set1: [X]m	LCSA:Set2: [X]m	LCSA:Set3: [X]m
100	98	97
LSCA:Set1: [Y]m	LCSA:Set2: [Y]m	LCSA:Set3: [Y]m
97	98	99
LCSA:Set1: [X]k	LCSA:Set2: [X]k	LCSA:Set3: [X]k
97	97	112
LCSA:Set1: [Y]k	LCSA:Set2:[Y]k	LCSA:Set3: [Y]k
95	98	99
Economic indicators (5%)		
LCSA:Set1: [X]m	LCSA:Set2: [X]m	LCSA:Set3: [X]m
96	97	97
LSCA:Set1: [Y]m	LCSA:Set2: [Y]m	LCSA:Set3: [Y]m
96	95	95
LCSA:Set1: [X]k	LCSA:Set2: [X]k	LCSA:Set3: [X]k
97	96	112
LCSA:Set1: [Y]k	LCSA:Set2:[Y]k	LCSA:Set3: [Y]k
96	95	95
Social indicators (5%)		
LCSA:Set1: [X]m	LCSA:Set2: [X]m	LCSA:Set3: [X]m
95	97	96
LSCA:Set1: [Y]m	LCSA:Set2: [Y]m	LCSA:Set3: [Y]m
96	97	95
LCSA:Set1: [X]k	LCSA:Set2: [X]k	LCSA:Set3: [X]k
96	96	98
LCSA:Set1: [Y]k	LCSA:Set2:[Y]k	LCSA:Set3: [Y]k
95	96	96